

Summary of CARB Diesel-CNG Transit Bus Emissions Project Phase 1A Panel Mode (Single Diameter) SMPS Data

**Britt A. Holmén, Principal Investigator
M. Katherine Nanzetta-Converse, Research Assistant**

University of California, Davis

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**Alberto Ayala
California Air Resources Board**

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Table of Contents

1	INTRODUCTION	3
2	METHODS.....	4
3	RESULTS FOR EACH INDIVIDUAL SAMPLE	5
3.1	Results by bus.....	5
3.1.1	Baseline Diesel Bus	5
3.1.2	CNG bus.....	6
3.1.3	Trap Diesel.....	9
3.2	Results by driving cycle.....	11
3.2.1	CBD Cycle.....	11
3.2.2	UDDS Cycle	12
3.2.3	NY Bus Cycle	13
 APPENDIX A: SCANNING MOBILITY PARTICLE SIZER (SMPS) PANEL MODE RAW DATA PROCESSING PROCEDURES.....		 15
A.1	INTRODUCTION.....	15
A.2	THE SCANNING MOBILITY PARTICLE SIZER INSTRUMENT	15
A.2.1	Electrical Mobility.....	15
A.2.2	Charging Probability	16
A.2.3	Transfer Function	17
A.3	PANEL DATA CONVERSION METHOD: RAW CPC COUNTS TO CONCENTRATIONS	19
A.3.1	Correction Factor for DMA	19
A.3.2	Corrections for System Flow Rates and CPC	19
A.4	VISUAL BASIC MACRO FOR MICROSOFT EXCEL	22
A.5	REFERENCES CITED	25
 APPENDIX B: SCANNING MOBILITY PARTICLE SIZER (SMPS) PANEL MODE DATA NUMBER CONCENTRATION PLOTS BY INDIVIDUAL DRIVING CYCLE.....		 26

1 Introduction

This document provides an overview of the single diameter “panel mode” SMPS data collected in Phase 1A of the MTA diesel-CNG transit bus testing study. It includes preliminary observations and plots of every driving cycle sample collected in panel mode during this part of the study. A master data file containing all formatted data and the visual basic code for the macro used to format that data are provided in electronic format.

During Phase 1A of CARB’s heavy-duty transit bus testing project at MTA, panel mode SMPS data were measured simultaneously at two locations that had different dilution conditions – CVS tunnel and ejector diluter minidiluter—at six mobility diameters (8, 20, 50, 80, 100 and 140 nm), for three driving cycles (CBD, UDDS, NY Bus, Figure 1), using three bus configurations (baseline diesel, CNG, and trap-equipped diesel). The CNG bus was retested almost 3 months after the initial CNG testing; these data are referred to as the “CNG-retest” data in this report.

A total of 57 single diameter driving cycle “samples” were collected (Table 1). Dates and times of sampling are detailed in the *PanelMaster.xls* data file and were taken from the field sampling logs. For this document, ‘sample’ refers to a driving cycle sample whereas ‘scan’ refers to an individual SMPS scan. Note that multiple scans comprise a given sample (driving cycle).

Table 1: Number of samples by diameter, driving cycle and bus. Buses were the CNG (CNG and CNG-retest), baseline diesel (BASE), trap-equipped diesel (TRAP)

Diameter	Vehicle	# CBD samples	# NY Bus samples	# UDDS samples	# samples per diameter
8	CNG	1	0	0	9
8	Base	1	0	0	
8	TRAP	2	1	2	
8	CNG-retest	2	0	0	
20	CNG	1	0	0	14
20	Base	1	0	0	
20	TRAP	3	3	0	
20	CNG-retest	2	2	2	
50	CNG	0	0	0	2
50	Base	0	0	0	
50	TRAP	0	0	2	
50	CNG-retest	0	0	0	
80	CNG	1	0	0	15
80	Base	0	0	0	
80	TRAP	3	3	2	
80	CNG-retest	2	2	2	
100	CNG	0	0	0	2
100	Base	0	0	0	

Diameter	Vehicle	# CBD samples	# NY Bus samples	# UDDS samples	# samples per diameter
100	TRAP	0	0	2	
100	CNG-retest	0	0	0	
140	CNG	1	0	0	15
140	Base	0	0	0	
140	TRAP	3	3	2	
140	CNG-retest	2	2	2	
Total		25	16	16	Grand Total: 57

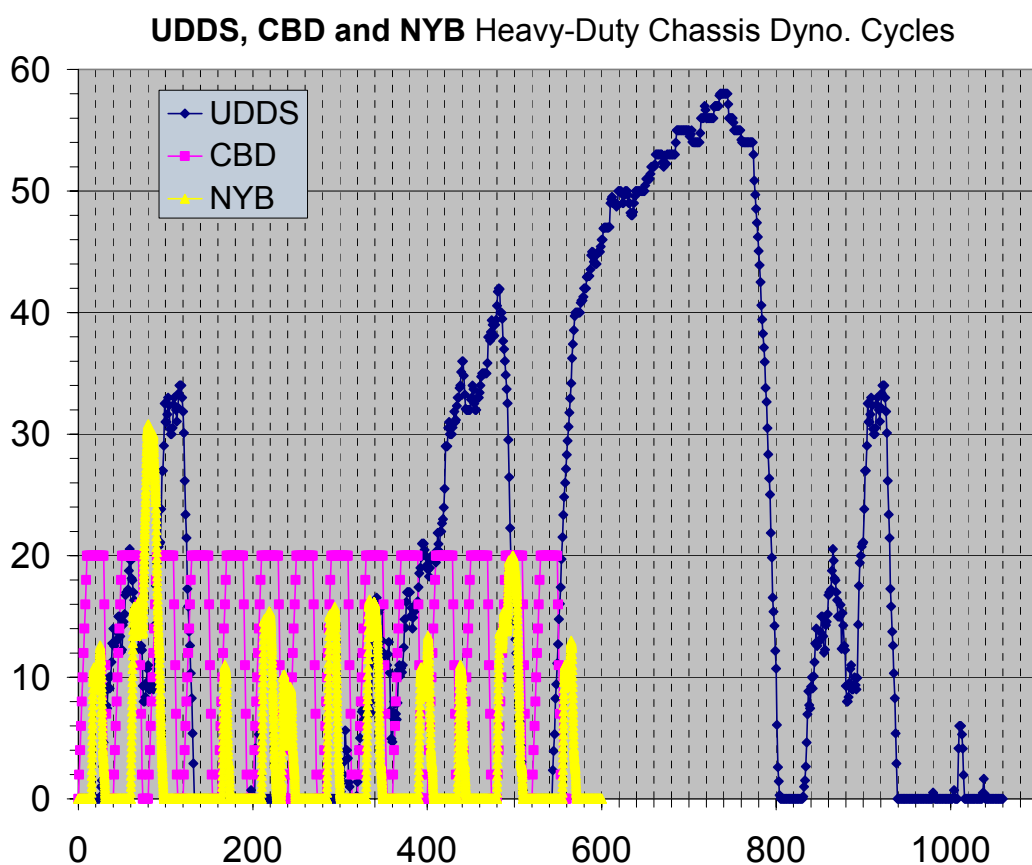


Figure 1: Driving cycles used for panel mode data collection during ARB's MTA Phase 1A testing.

2 Methods

Two data processing steps were used to convert the raw SMPS data to the format presented here. First, data from scans containing panel mode data (exported using AIM software version 5.2.0 with the 'raw counts' option box selected) were assigned to correspond to individual driving cycles. Second, these data were converted from raw counts to number concentrations using correction factors derived using the procedures

outlined in Appendix A. The corrected data are plotted individually in Appendix B by bus and cycle.

Both data processing steps were performed using a specially-created macro (see Appendix A.4). The macro performs the following tasks:

- Assembles SMPS scans taken in panel mode into samples corresponding to driving cycles.
- Converts raw CPC counts (on 0.1 second intervals) to number concentrations on 1 second intervals based on flow rates and diameter (voltage) setting on DMA.
- Outputs raw and converted data in order to trace program activity while also providing formatted panel data.
- Minidiluter data were adjusted for dilution ratio by multiplying by 65.
- CVS data were not adjusted for dilution.

User input to the macro includes the definition of each SMPS scan number and second number in the scan that correspond to a given particle diameter in each sample (driving cycle).

3 Results for each individual sample

3.1 Results by bus

The average number concentrations for each sample were computed and plotted in a bar chart as an overview of results by diameter and driving cycle for each bus. Key observations are based on the plots of every panel mode sample (number concentration versus time), provided in Appendix B. All of the Appendix B figures are not corrected for dilution and figure names are given in italics. As seen in Appendix B, 12 figures are included for each SMPS (e.g., the CVS sampling location and the minidiluter sampling location were sampled with the orange and purple SMPSs, respectively), some with multiple subplots. For example, *Figure 1 Minidiluter* and *Figure 1 CVS* present the data from the same driving cycle measured simultaneously on each SMPS.

3.1.1 Baseline Diesel Bus

The only single-diameter baseline diesel bus data was collected on the CBD driving cycle, one sample was collected at 8 nm and the other at 20 nm.

3.1.1.1 BASE-CBD cycle

For both the minidiluter and the CVS locations (Figure 2) the number concentrations for $D_p = 20$ nm were much higher compared with $D_p = 8$ nm. The plots of number concentration versus time are given in Appendix B (*Figure 1 CVS*, *Figure 1 Minidiluter*). From the Appendix B figures, the lower concentration 8 nm data (for both CVS and minidiluter) appears to have more noise and is less smooth than the 20 nm data. Peaks in the number concentration data that mirror peaks in the speed-time trace of the CBD can be seen in the CVS samples and in the 20 nm minidiluter sample.

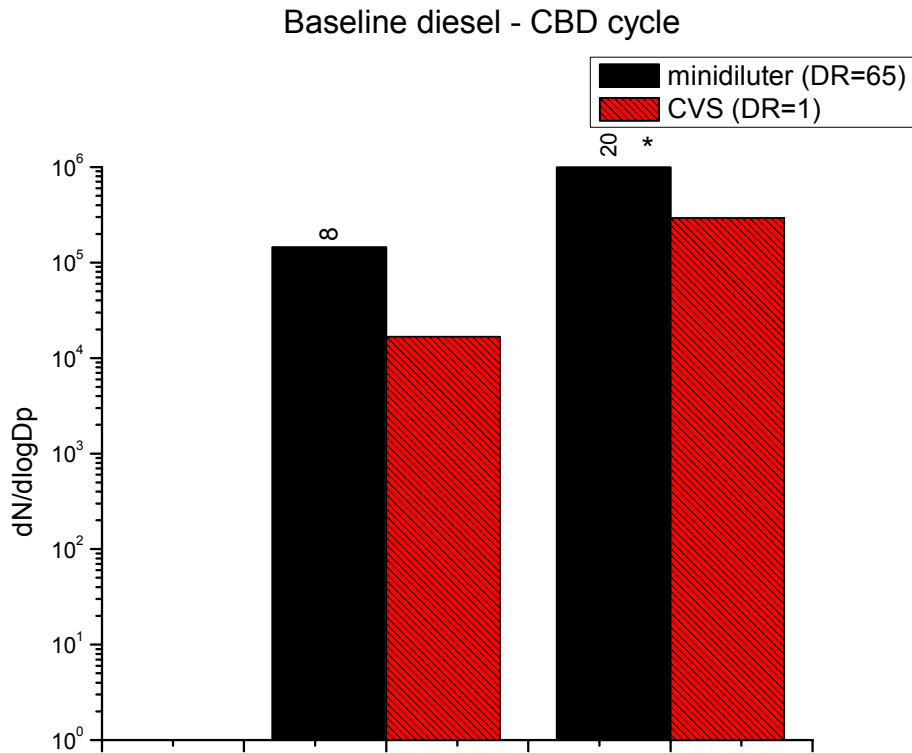


Figure 2: Average of number concentration over each driving cycle sample measured in the exhaust of the baseline diesel in phase 1A of the MTA ARB study. Asterisks denote the sample contained an SMPS scan with the error, “CPC laser, flow or temperature out of range” reported in the status field.

3.1.2 CNG bus.

Panel mode samples were collected for the CNG bus on all three driving cycles. The CNG-retest data was collected in June and earlier samples were collected in March.

3.1.2.1 CNG-CBD cycle

CNG panel mode data at diameters 8, 20, 80, and 140 nm were measured on the CBD driving cycle on March 23 and June 7. On June 7, two samples were collected at each diameter whereas on March 23 one sample was collected at each diameter. Therefore each figure for the CNG bus on the CBD cycle has 3 subplots (*Figures 2 – 5, Appendix B*). On March 23, samples were measured in order of increasing diameter (8, 20, 80, 140 nm) and on June 7 samples were measured in increasing, then decreasing diameter (8, 20, 80, 140, 140, 80, 20, 8 nm). The warm-up in March, consisted of two warm-up periods, each for 11 minutes. The warm-up on June 7 was also two periods, first 3 minutes and then 18 minutes.

Overall, number concentrations on the CBD cycle from the CNG bus were greater at the measured diameters in June compared to March, reflecting the lower dilution ratio (DR=18) used in June sampling compared to March (DR=65). In addition, the June data samples collected later in the day had relatively lower concentrations than the earlier

measured data. This effect may have occurred because the bus had been running longer and was more warmed up. (Note that data from NY Bus driving cycle demonstrate the opposite trend with respect to time of day as discussed below.) Peaks in number concentrations mirror the peaks in speed of the CBD driving cycle and the CVS and minidiluter results revealed similar patterns.

Figure 2 CVS and Figure 2 Minidiluter present the 8 nm data collected on the CNG bus running on the CBD driving cycle and each contain 3 subplots. The single March 23 sample had the lowest number concentrations whereas substantially higher concentrations were measured for the first of two 8 nm test on June 7. The second 8 nm test on June 7 was about 2 hours later than the first and had much lower concentrations than the first test on that day.

The 20 nm results (*Figure 3 CVS and Figure 3 Minidiluter*) were very similar to the 8 nm results discussed above. That is, the first 20 nm sample had much larger number concentrations than the second sample on June 7 and both June samples had higher number concentrations than the March 23 sample.

The two June 7 samples of 80 and 140 nm number concentrations were more similar to each other (*Figure 4 CVS, Figure 4 Minidiluter, Figure 5 CVS, Figure 5 Minidiluter*). Note that by the time the 80 nm and 140 nm data were collected (based on the June sampling order for CBD cycle with the CNG bus, previously noted), the bus had been running longer (compared to the 8 and 20 nm data).

The plot of average number concentrations measured in CNG exhaust on the CBD cycle show the sample-to-sample variation that was discussed in detail above (Figure 3).

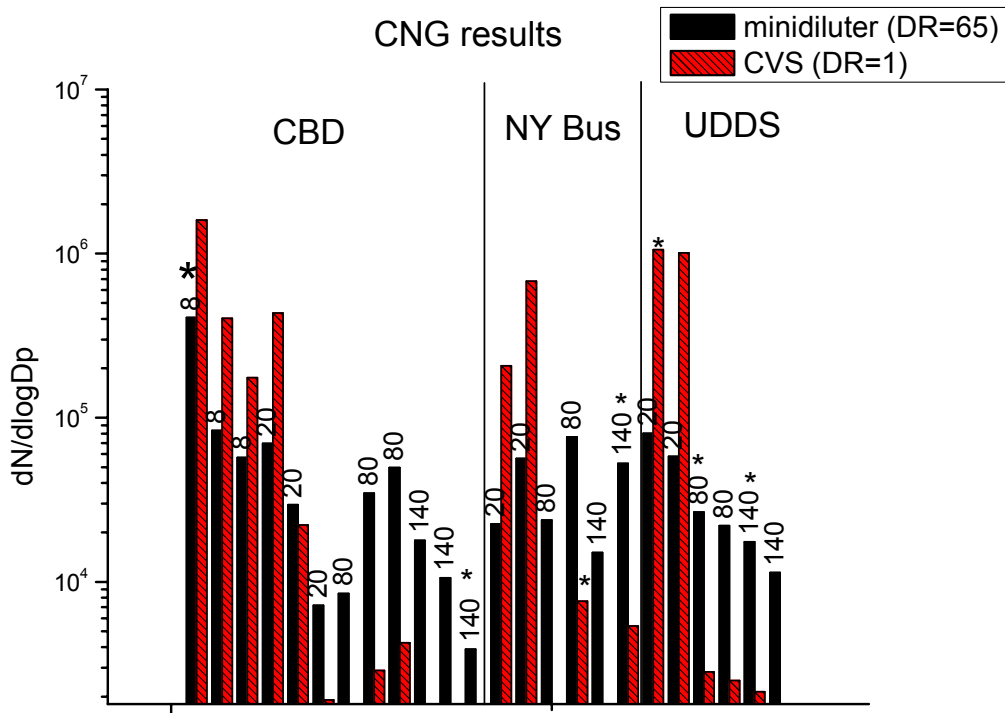


Figure 3: Average of number concentration over each driving cycle sample measured in the exhaust of the CNG bus in phase 1A of the MTA ARB study. Asterisks denote the sample contained an SMPS scan with the error, “CPC later, flow or temperature out of range” reported in the status field.

3.1.2.2 CNG-NY Bus cycle

CNG panel mode data at diameters 20, 80, and 140 nm were collected on the NY Bus driving cycle on June 8 with two samples at each diameter. On June 8, samples were measured in order of decreasing, then increasing diameter (140, 80, 20, 20, 80, 140 nm) and on June 7 samples were measured in increasing, then decreasing diameter (8, 20, 80, 140, 140, 80, 20, 8 nm). The CNG bus was warmed up for more than 30 minutes on June 8 prior to panel mode sampling.

Figure 6 CVS and Figure 6 Minidiluter contain the data measured from the CNG bus on the NY Bus driving cycle. The second sample for each diameter had substantially larger concentrations than the first sample at the corresponding diameter. This result is the opposite as was observed for the CBD cycle, as previously described. Peaks in measured number concentration for the second set of samples were clearly seen at all diameters and mirrored the peaks in speed of the NY Bus driving cycle. The first set of samples also had visible peaks for some of the speed peaks of the cycle, but the peaks were not distinctly apparent for each peak of speed as was seen in the second set of samples at each diameter.

Again, the plot of average number concentrations measured in CNG exhaust on the NY Bus cycle show the sample-to-sample variation as discussed in detail above (Figure 3).

3.1.2.3 CNG-UDDS cycle

On June 12, two CNG panel mode samples were collected at each diameter for 20, 80, and 140 nm on the UDDS driving cycle. The order of sampling was yet again different from the previous driving cycles sampled with this bus. Specifically, on June 12, samples were measured in pairs in order of decreasing diameter (140, 140, 80, 80, 20, 20 nm). The CNG bus was warmed up for more than 20 minutes on June 12 prior to panel mode sampling.

For the 20 and 80 nm data, each pair of samples was very similar in terms of number concentrations (*Figure 7 CVS, Figure 7 Minidiluter*). In contrast, the second sample of 140 nm particles had somewhat lower concentrations than the first sample at that particle size. Referring to the order of samples, this result may have occurred because the 140 nm data were collected first and the CNG was more warmed-up during collection of the second UDDS cycle at 140 nm. Number concentrations of 20 nm particles were greatest, and concentration decreased with increasing diameter (note that the y-axis scale is not constant in *Figure 7*). As seen in the CBD and NY Bus results, the pattern of peaks in the speed-time trace of the driving cycle was similar to the peaks in the number concentration data.

The plot of average number concentrations measured in CNG exhaust on the UDDS cycle show that average number concentrations on this driving cycle appear more consistent from sample to sample than the CBD and NY Bus cycles (*Figure 3*).

3.1.3 Trap Diesel

For the trap diesel bus (TRAP), panel mode data was collected on the CBD, NY Bus, and UDDS driving cycles.

3.1.3.1 TRAP-CBD cycle

The trap diesel was tested on the CBD cycle over two days, May 2 (8 samples, two at each diameter of 8, 20, 80, and 140 nm) and May 11 (3 samples, one at 20, 80 and 140 nm). On May 2, the bus had driven multiple CBDs prior to the panel mode testing. On May 11, a 'warm up' was run for more than 15 min. Note that the minidiluter dilution ratio on May 11 was lower than for all previous sampling days. It was reduced from DR=65 to DR=18 in order to examine the effects of dilution ratio on particle emissions.

Number concentrations for $D_p = 8$ nm in trap diesel exhaust running on the CBD driving cycle were very low (*Figure 8 CVS, Figure 8 Minidiluter*) and no peaking pattern corresponding to peaks in the speed of the driving cycle were apparent. However, peaks in number concentrations that mirror peaks in the speed-time trace of the CBD were evident in the 20, 80, and 140 nm data (*Figure 9 CVS, Figure 9 Minidiluter*).

On May 2, consistent number concentrations were measured for each pair of samples at each given diameter. As expected due to changes in the minidiluter dilution ratio, number concentrations on May 11 were greater than May 2. Particularly the first tests on May 11 had substantially greater number concentrations, for 140 and 80 nm (note scales on *Figure 9 CVS and Figure 9 Minidiluter* subplots).

3.1.3.2 TRAP-NY Bus cycle

The trap diesel bus was tested on the NY Bus cycle over two days, May 8 (7 samples, two at each diameter of 20, 80, and 140 nm and one at $D_p = 8\text{nm}$) and May 11 (3 samples, one at 20, 80 and 140 nm). On May 2, the bus had driven multiple CBDs prior to the panel mode testing. On May 11, a 'warm up' was run for more than 15 min.

Very low number concentrations of 8 nm particles were measured from the trap diesel on the NY Bus cycle (*Figure 10 CVS*, *Figure 10 Minidiluter*). Very similar results were observed for each of the three samples at $D_p = 20, 80,$ and 140 nm in the CVS data (*Figure 11 CVS*). The minidiluter data had larger concentrations measured on May 11 at $D_p = 20, 80,$ and 140 nm compared with May 2 due to the change in the minidiluter dilution ratio.

3.1.3.3 TRAP-UDDS cycle

The trap diesel was tested on the UDDS cycle over two days, May 9 (4 samples, two at $D_p = 80,$ and 140 nm) and May 10 (6 samples, two each at $D_p = 8, 50$ and 100 nm). On May 2, the bus had driven multiple CBDs prior to the panel mode testing. On May 11, a 'warm up' was run for more than 15 min.

For each diameter, each pair of samples was generally consistent in magnitude. Interestingly, number concentrations measured in the CVS at $D_p = 8\text{ nm}$ had a large peak corresponding to the highest speed portion of the UDDS (*Figure 12 CVS*). This differs from the other driving cycles for this bus and for all buses. Previous 8 nm samples did not have such large number concentrations. Also, $D_p = 8\text{ nm}$ minidiluter UDDS sample did not have corresponding patterns to the samples collected in the CVS tunnel.

As with the CNG bus, more consistent number concentrations were measured for the UDDS driving cycle compared with the CBD or NY Bus driving cycle (Figure 4).

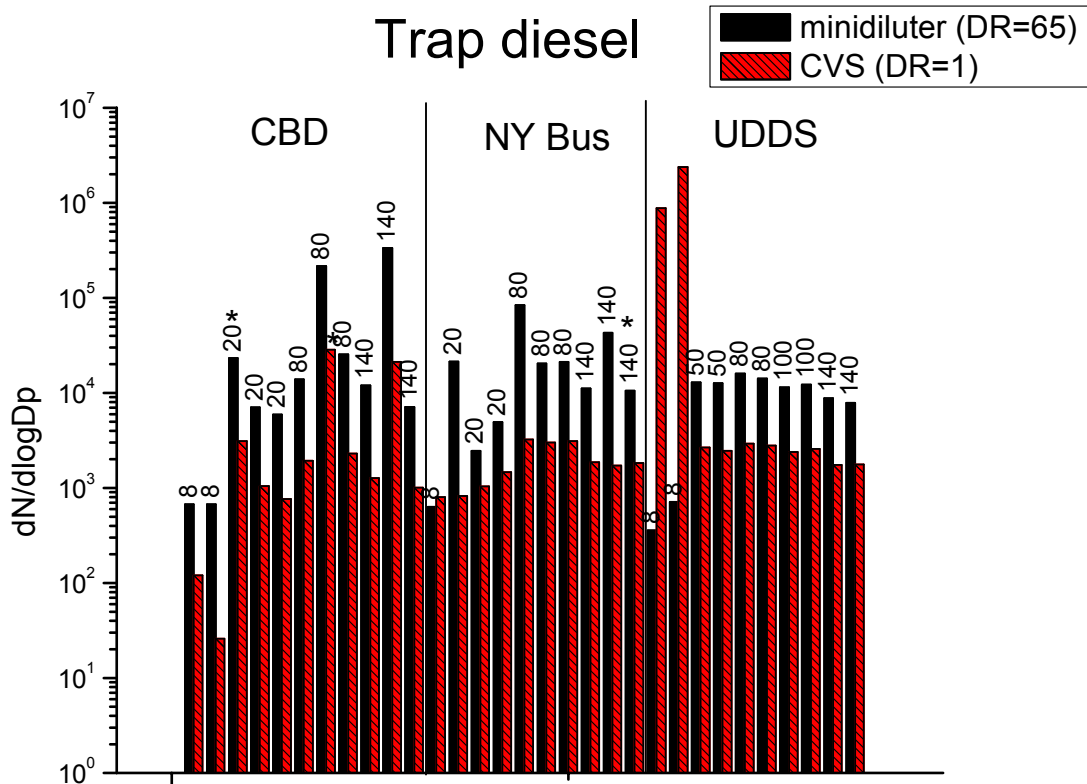


Figure 4: Average of number concentration over each driving cycle sample measured in the exhaust of the trap diesel bus in phase 1A of the MTA ARB study. Asterisks denote the sample contained an SMPS scan with the error, “CPC later, flow or temperature out of range” reported in the status field.

3.2 Results by driving cycle

In this section, the results from each bus at each diameter are compared for each of the three driving cycles that had panel mode data (CBD, UDDS, NY Bus) and between sampling locations.

3.2.1 CBD Cycle

For 21 of the 25 sample pairs collected on the CBD driving cycle, number concentrations measured in the CVS tunnel were lower than number concentrations measured in the minidiluter (corrected for dilution, Figure 5). The four samples with higher CVS concentrations were from the CNG bus: all three samples of 8 nm particles and one of the samples of 20 nm particles. Six samples had an SMPS scan with the error of CPC laser, flow or temperature reported in the status field of the scan, two from the CVS location and four from the minidiluter location. The trap diesel (T) had much lower number concentrations of 8 nm particles compared with the baseline diesel (B) and CNG buses and, although there was more variation, generally had lower concentrations of 20 nm particles compared with the CNG bus. There was greater variation in 80 and 140 nm

number concentrations from sample to sample for the trap diesel (T) and CNG buses (no baseline diesel samples collected for these diameters) and it is not clear that one bus emitted larger concentrations over the other for those particle sizes.

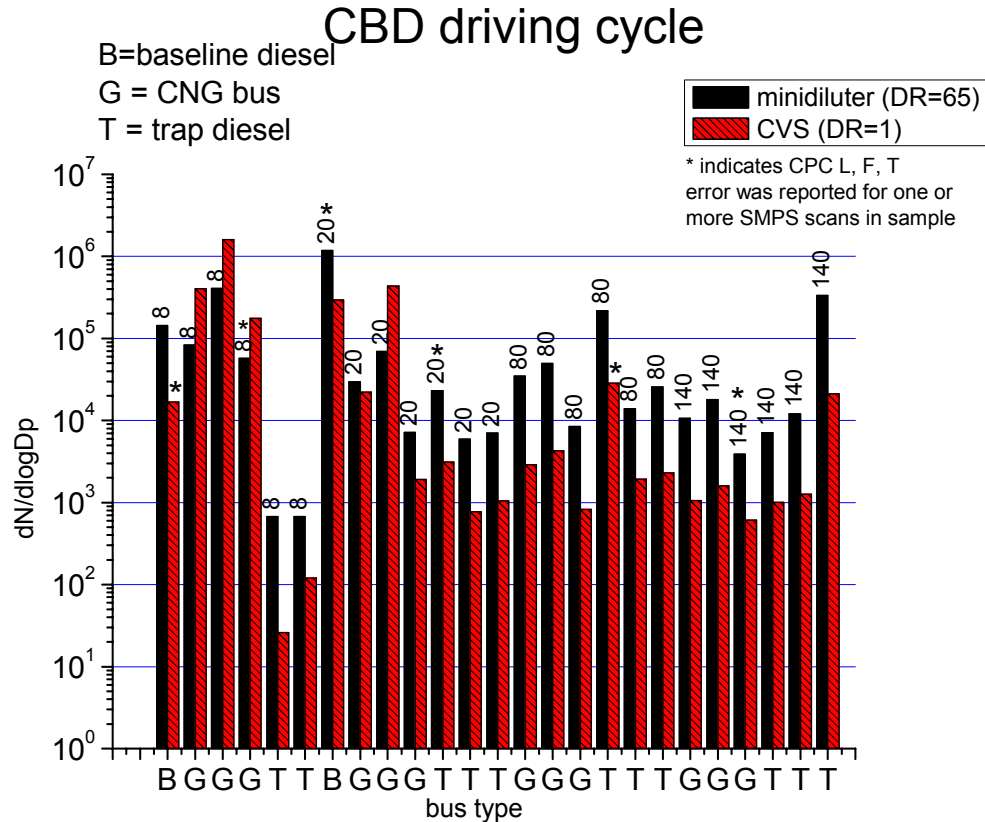


Figure 5: Average number concentrations for each sample (driving cycle) on the CBD driving cycle. Labels indicate diameter setting during test, key on figure. Asterisks denote the sample contained an SMPS scan with the error, “CPC laser, flow or temperature out of range” reported in the status field.

3.2.2 UDDS Cycle

Of the fifteen pairs of samples taken on the UDDS driving cycle, minidiluter number concentrations were larger than CVS concentrations for all but four pairs, measured at the smaller diameters (8 and 20 nm; Figure 6). Two minidiluter samples and one CVS sample had the CPC flow, laser or temperature error reported in the status field for one of the scans of the sample.

UDDS driving cycle

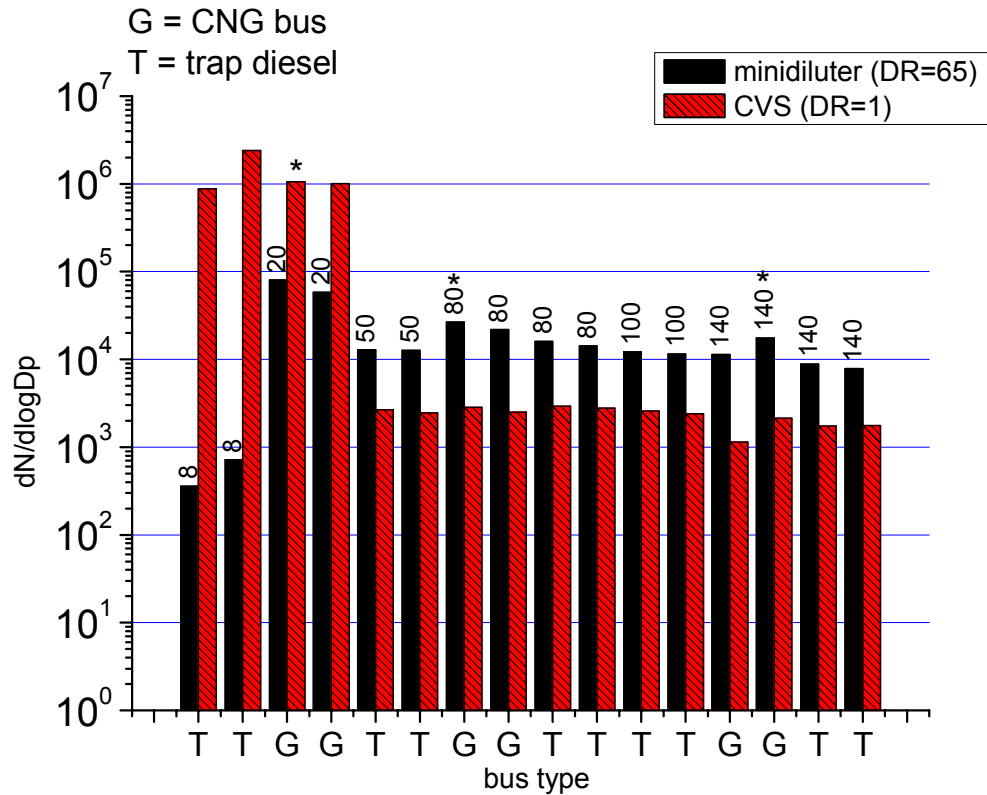


Figure 6: Average number concentrations for each sample (driving cycle) on the UDDS driving cycle. Labels indicate diameter setting during test. Asterisks denote the sample contained an SMPS scan with the error, “CPC laser, flow or temperature out of range” reported in the status field.

3.2.3 NY Bus Cycle

Just as was seen for the UDDS driving cycle, of the sixteen pairs of samples taken on the NY Bus driving cycle, minidiluter number concentrations were larger than CVS concentrations for all but three pairs, measured at the smaller diameters (8 and 20 nm; Figure 7). Two minidiluter samples and one CVS sample had the CPC flow, laser or temperature error reported in the status field for one of the scans of the sample.

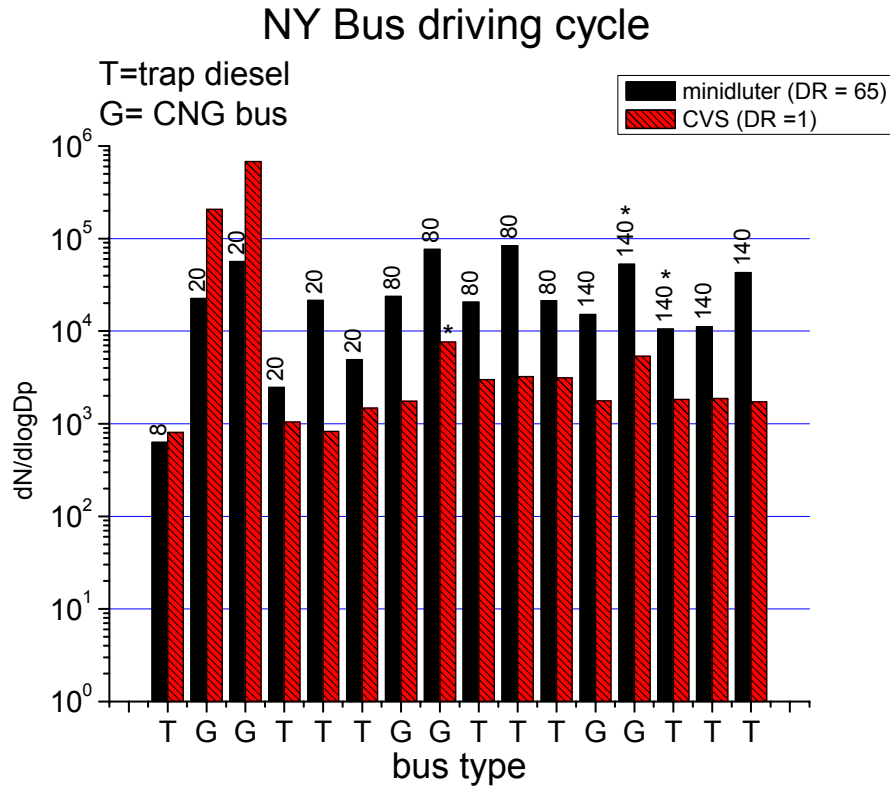


Figure 7: Average number concentrations for each sample (driving cycle) on the UDDS driving cycle. Labels indicate diameter setting during test. Asterisks denote the sample contained an SMPS scan with the error, “CPC laser, flow or temperature out of range” reported in the status field.

Appendix A: Scanning Mobility Particle Sizer (SMPS) Panel Mode Raw Data Processing Procedures

A.1 Introduction

This document provides some details on SMPS operation, and conversion of the panel mode data type. The sections were taken from the dissertation, “Roadside Ultrafine and Nanoparticle Particle Number Distributions in Northern Central Valley, CA and Relationships to Meteorology and Traffic” (Nanzetta, 2004).

A.2 The Scanning Mobility Particle Sizer Instrument

The Scanning Mobility Particle Sizer (SMPS), commercially available from TSI, Inc. (St. Paul, MN), was used for this research and is described in this section. In addition, TSI’s SMPS has been widely used by many researchers.

The SMPS measures particle number concentrations and size distributions for submicron particles (TSI Inc 2002a) and consists of two components: a differential mobility analyzer (DMA) and a condensation particle counter (CPC). The size range measured depends on the model of the two components and the operational configuration. Multiple models of the DMA and the CPC are available from TSI and each design has different capabilities. Flow rates, scan times, and the inlet impactor are configurable and also determine the size range measured by the SMPS.

Prior to entering the DMA, particles are charged while passing through a Kr-85 bipolar charger. Brownian motion, or diffusion, of the particles results in frequent collisions between particles and ions in the charger, this brings the aerosol to a certain charge distribution described by Fuchs theory (1963). The charged particles are exposed to an electric field in the DMA, generated by the voltage on the center rod. The DMA rod voltage is scanned through a range, guiding selected particle sizes through a slit near the bottom of the rod. The computer controls the range of DMA voltages that are scanned during collection of a single size distribution. The SMPS user also selects a duration (“scan time”) over which the size distribution will be collected. The particles that exit the DMA slit are then counted by the CPC.

The Ultrafine CPC (UCPC 3025A) uses butanol heterogeneous condensation to grow particles to a diameter large enough to be detected by an optical particle detector. A band of laser light above the aerosol exit nozzle with dimensions 10 μm by 2 mm is formed in the optical detector by focusing of the laser diode beam via a collimating lens and a cylindrical lens (TSI Inc 2002b). When a particle goes through the beam the signal is not detected, indicating a particle blocked it momentarily. These particle counters (CPC) can be used in a standalone mode for particle counting without sizing, referred to as an integrated measurement.

A.2.1 Electrical Mobility

The SMPS separates particles of different sizes on the basis of electrical mobility (Z_p) and uses optical (light scattering) techniques to count the particles. Electrical mobility

describes the motion of a charged particle in an electric field, such as within the DMA. A particle with n elementary units of charge, in an electric field (E) will experience a force (F) proportional to the field strength (Equation A.1).

Equation A.1: Electrostatic force on a charged particle in electric field (Seinfeld and Pandis 1998).

$$F = n * E$$

The steady-state migration velocity of a charged particle in an electric field (v_e) is determined by the balance between the drag force and the electrostatic force (in a quiescent fluid) (Equation A.2).

Equation A.2: Velocity of a particle in an electric field (Seinfeld and Pandis 1998).

$$v_e = Z_p * E$$

Electrical mobility (Z_p) is a function of the number of charges on a particle (n , as defined above), the mobility diameter (D_p), the viscosity of the air (μ), the Cunningham slip correction factor (C_c), and the unit of elementary charge (q_e) (Equation A.3).

Equation A.3: Electrical mobility (TSI Inc 2002).

$$Z_p(D_p) = \left[\frac{q_e * n * C_c(\lambda, D_p)}{3 * \pi * \mu * D_p} \right]$$

The Cunningham slip correction factor is a function of the mean free path of the fluid (i.e., air, λ) and particle diameter based on a spherical particle of diameter D_p (Equation A.4, Seinfeld and Pandis 1998). Recall that Z_p was the constant of proportionality between a particle's migration velocity and the electric field intensity. The migration velocity is defined by Stokes' law which describes the drag force on a particle moving in a fluid, and applies to particles of diameter much larger than the mean free path of the fluid. To account for very small diameter particles, C_c adjusts for the noncontinuum effects that arise when particle size approaches the magnitude of the mean free path of air.

Equation A.4: Cunningham slip correction factor (Seinfeld and Pandis 1998).

$$C_c = 1 + \frac{2\lambda}{D_p} * \left[1.257 + 0.400 * \exp \left[\frac{-1.1 * D_p}{2\lambda} \right] \right]$$

A.2.2 Charging Probability

The sample aerosol passes through a Kr-85 bipolar charger where particles are bombarded with bipolar ions and are brought to an equilibrium charge distribution. The distribution can be described as the probability of a particle of a given size having a certain charge. For particles of diameter $1 \text{ nm} < D_p < 1000 \text{ nm}$, the probability of a particle having a charge n ($f(n, D_p)$) is computed using an approximation to Fuch's theory as specified by Wiedensohler (1988).

Equation A.5: Probability of charge, n on particle of diameter D_p (Wiedensohler 1988).

$$f(n, D_p) = 10^{\left(\sum_{i=0}^5 a_{i,n} * \log \left(\frac{D_p}{\text{nanometers}} \right) \right)^i}$$

where:

$$a_{n=-2} = \begin{Bmatrix} -26.3328 \\ 35.9044 \\ -214608 \\ 7.0867 \\ -1.3088 \\ 0.1051 \end{Bmatrix}, \quad a_{n=-1} = \begin{Bmatrix} -2.3197 \\ 0.6175 \\ 0.6201 \\ -0.1105 \\ -0.1260 \\ 0.0297 \end{Bmatrix}, \quad a_{n=0} = \begin{Bmatrix} -0.0003 \\ -0.1014 \\ 0.3073 \\ -0.3372 \\ 0.1023 \\ -0.0105 \end{Bmatrix},$$

$$a_{n=1} = \begin{Bmatrix} -2.3484 \\ 0.6044 \\ 0.4800 \\ 0.0013 \\ -0.1553 \\ 0.0320 \end{Bmatrix}, \quad a_{n=2} = \begin{Bmatrix} -44.4756 \\ 79.3772 \\ -62.8900 \\ 26.4492 \\ -5.7480 \\ 0.5049 \end{Bmatrix}$$

For particles in the size range measured by the SMPS it is with the greatest probability that particles will have a +1 charge. Based on this assumption, the column matrix $a_{n=1}$, above, can be used in

Equation A.5 to compute the charging probability for a given diameter, D_p , by computing $(f(1, D_p))$.

A.2.3 Transfer Function

The transfer function (\mathcal{Q}) is the probability that a particle of a given electrical mobility will be selected by the DMA and exit to the CPC to be counted (Knutson and Whitby 1975). After passing through the bipolar charger, the aerosol sample flows into the DMA. Inside the DMA, clean sheath air forces the inlet aerosol to flow downward along the outer wall of the DMA. The charged particles move toward the center rod because the voltage on the rod produces an attractive electric force. Whether or not particles pass through a small opening at the bottom of the DMA and proceed to the CPC for counting depends on DMA geometry, the aerosol and sheath air flow rates, and the drag and electrostatic forces on a given particle. Thus, the aerosol and sheath flow rates (q_a , q_c respectively) and the voltage on the DMA center rod (V) determine the particle electrical mobility diameter that will make it through the opening. The transfer function was theoretically determined through an analysis of particle streamlines within the DMA (Knutson and Whitby 1975).

Because the opening in the DMA rod is of finite width, there is a range of diameters (and corresponding electrical mobilities, Z_p) that pass through the opening. Particles centered

around the mobility midpoint ($Z_p^*(D_p)$), will exit the DMA for a given voltage and flowrate. This range is defined in mobility space as the mobility bandwidth ($\Delta Z_p(D_p)$), Figure A.1). The lower bound is defined as $Z_p(D_{lower})$ and the upper bound is $Z_p(D_{upper})$.

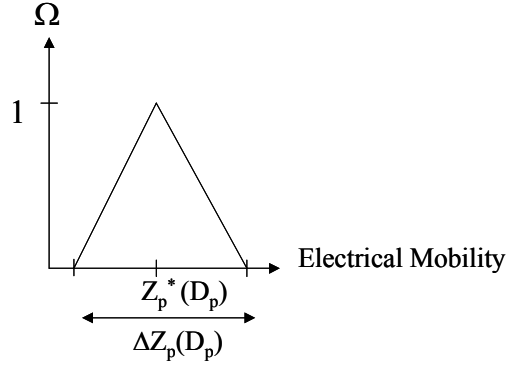


Figure A.1: Transfer function for DMA (Knutson and Whitby 1975)

In diameter space, the width of the transfer function in diameter space (ΔD_p) is expressed as the difference between the diameter at the upper limit and the diameter at the lower limit (Equation A.6).

Equation A.6: Transfer function width in diameter space.

$$\Delta D_p = D_{upper} - D_{lower}$$

To determine the width of the transfer function in diameter space, the upper and lower diameter limits of the transfer function must be computed (D_{upper}, D_{lower}), as follows. For the present research, the diameter corresponding to the voltage, aerosol and sheath flow rates (V, q_a, q_c , respectively) was known. Thus, the slip correction factor can be computed using Equation A.4, given the diameter corresponding to the voltage setting on the DMA (D_p). Next, $Z_p(D_p)$ (electrical mobility) can be computed (Equation A.3). The electrical mobilities at the upper and lower diameter limits ($Z_p(D_{upper}), Z_p(D_{lower})$) of the transfer function can be solved for using the two root equations given in Equation A.7.

Equation A.7: Root equations for transfer function parameters.

$$\frac{Z_p(D_p)}{Z_p(D_{upper})} - \left(1 + \frac{q_a}{2 * q_c}\right) = 0; \frac{Z_p(D_p)}{Z_p(D_{lower})} - \left(1 - \frac{q_a}{2 * q_c}\right) = 0$$

Then, using Equation A.3 and Equation A.4 D_{lower} and D_{upper} are found. Referring to Equation A.3 we see that Z_p is defined in terms of C_c and D_p . Also note that C_c depends on D_p , as defined in Equation A.4. Thus, a simultaneous set of equations must be solved to determine ΔD_p and ultimately define the transfer function for the SMPS given the specified voltage and flow conditions.

A.3 Panel Data Conversion Method: Raw CPC Counts to Concentrations

For samples collected in panel mode, the raw CPC count data must be converted to particle number concentrations. A conversion factor (CF) was computed to account for the non-finite mobility band inherent in the DMA (discussed in Chapter 2). The CF is based on the transfer function of the DMA, and the charging probability for a given particle diameter and was implemented in a Mathcad program. The charging probability and transfer function for the SMPS was described elsewhere (refer to Chapter 2 for equations and discussion). The method and assumptions involved in calculating the CF for panel mode data, are described here. Refer to Chapter 1 for additional details on electrical mobility, charging probability, and the SMPS transfer function.

A.3.1 Correction Factor for DMA

The equation to convert raw CPC counts ($CPCcount_{0.1-sec}$) to number concentrations in units of $dN/d\log D_p$ for a given diameter (D_p) involves two major steps. First, using the width of the transfer function in diameter space (ΔD_p), and the charging probability for a charge of +1 ($f(1, D_p)$) the correction factor for the number of particles exiting the DMA is computed, as described in Equation A.8. Mathcad was used to solve for ΔD_p using Equation A.6.

Equation A.8: Correction factor for DMA

$$CF = \frac{1}{f(1, D_p) * \log\left(\frac{\Delta D_p}{D_p} + 1\right)}$$

The conversion factors for each panel mode diameter used in this study were computed and are summarized in Table A.1. The second column of Table A.1 contains the conversion factors to compute a normalized particle concentration $dN/d\log D_p$ for the diameter settings used in this experiment.

Table A.1: Conversion factor to account for classifier mobility bandwidth and charging probability for specific diameter settings.

Diameter (nm)	Conversion Factor for $dN/d\log D_p$
10	1.133×10^3
20	542.565
30	375.142
40	300.145
70	216.752

A.3.2 Corrections for System Flow Rates and CPC

Given that the CF is used to account for classifier and DMA properties, the second step for the conversion is to take the raw count data from the exported file and compute particle counts in units of $\#/cm^3$. This step accounts for DMA output flow rate, CPC inlet flow rate and CPC aerosol sample flow rate. A diagram of the basic flows of the SMPS

pertinent to this discussion is shown in Figure A.2. In this experiment the aerosol flow rate (input to classifier) and the monodisperse aerosol flow rate (output from DMA) were equal to 1.4 LPM = $1400 \text{ cm}^3/\text{min}$. The CPC inlet flow in high flow mode used in this experiment is $1500 \text{ cm}^3/\text{min}$. Thus, at the inlet to the CPC, the DMA monodisperse aerosol was slightly diluted with a dilution factor of 0.933.

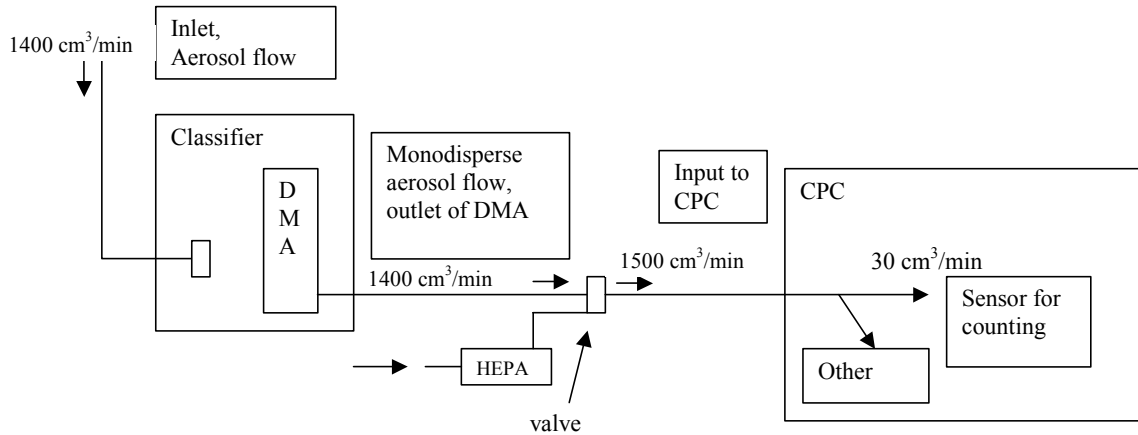


Figure A.2: Overview of flows in SMPS during sampling.

Also, the CPC sample flow internal to the 3025A has a flow rate of $30 \text{ cm}^3/\text{min}$, that is in one second 0.5 cm^3 of air travels through the sensor in the CPC for counting. An excerpt of raw data of duration 2.8 seconds that was exported from AIM and collected while the DMA voltage corresponded to 10 nm is shown in Table A.2. As an example the conversion the first second of that raw data to concentrations is shown in Equation A.9. The first term in the equation is the sum of raw counts for the first 10 rows, corresponding to second number one. As described above, the second ratio in Equation A.10 ($1500/1400$) arises from the dilution at the input to the CPC and because the flow rates used in this study were consistent throughout the sampling this ratio was also included for all of the panel data conversions. These flow rates will depend on system configuration. Refer to Figure A.2 to develop an appropriate conversion equation for a given setup.

Table A.2 Example of raw data exported from AIM in panel mode, collected with voltage setting corresponding to 10 nm diameter particles.

Raw Data Channel(s)	
0.1	8
0.2	4
0.3	3
0.4	2
0.5	2
0.6	1
0.7	5
0.8	4
0.9	5
1	2
1.1	4
1.2	5
1.3	5
1.4	1
1.5	4
1.6	3
1.7	5
1.8	2
1.9	4
2	4
2.1	4
2.2	1
2.3	2
2.4	4
2.5	2
2.6	3
2.7	1
2.8	4

Equation A.10. Example calculation of number of particles per cm^3 in dN/dlogDp based on raw data in table.

$$\frac{8 + 4 + 3 + 2 + 2 + 1 + 5 + 4 + 5 + 2}{\text{sec}} * \frac{1500 \text{ cm}^3/\text{min}}{1400 \text{ cm}^3/\text{min}} * \frac{1}{30 \text{ cm}^3/\text{min}} * 60 \text{ sec}/\text{min} * 1133 =$$

$$36 * 1.07 * 2 * 1133 * \frac{1}{\text{cm}^3} = 8.72 \times 10^4 \text{ particles}/\text{cm}^3$$

In summary, to convert the measured data, the following steps were taken. SMPS samples that were measured in panel mode were exported as text files from AIM software with the raw counts box selected. The resulting data file contained the CPC raw count data for each sample in 0.1-second increments. Panel mode samples were designated based on the diameter setting (DMA voltage) and the corresponding correction factor was computed using Mathcad. Raw counts were summed over one-second intervals and converted to concentrations based on CPC flow rates.

A.4 Visual Basic macro for Microsoft Excel

Attribute VB_Name = "Module1"

Sub panelprog()

Attribute panelprog.VB_Description = "panel data conversion from AIM format"

Attribute panelprog.VB_ProcData.VB_Invoke_Func = "d\n14"

' So far, this program writes the 0.1 second data into columns arranged by driving cycle

' input is the AIM output file with the driving cycle data embedded as shown in table below

' resulting data are included in same file as raw AIM data

' embedded cycle details in table of this format

' (excel columns-->) D E F G H I
' (text info included row2) cyclength 560
' (text info included row3) start sample sec # end sample sec# diameter DR
' (data row 3 to XX) 6 1 8 10 8nm 65
,

' see example file for further clarity of the above table

' next step is to sum 10 of the 0.1 second entries and multiply by the appropriate CF

'CALCULATE CONVERSION FACTORS FOR EACH DIAMETER

CPCinletflowrate = 1500

SMPSinletflowrate = 1450

CPCsensorflowrate = 30

numsecspermin = 60

diam8 = (1408) * (1500 / 1450) * (60 / 30)

diam20 = (524.306) * (1500 / 1450) * (60 / 30)

diam40 = (290.052) * (1500 / 1450) * (60 / 30)

diam50 = (250.277) * (1500 / 1450) * (60 / 30)

diam80 = (198.211) * (1500 / 1450) * (60 / 30)

diam100 = (184.152) * (1500 / 1450) * (60 / 30)

diam140 = (172.356) * (1500 / 1450) * (60 / 30)

start_col = 2

sample_row = 14

start_row = 147

smpls_sample_length = InputBox("SMPS sample length (up+down scan) in seconds")

numcycles = InputBox("enter number of driving cycles to be processed")

data_col = InputBox("number of cols of data in worksheet")

cyclelen = ActiveSheet.Cells(2, 5)

For cycleouterloop = 0 To (numcycles - 1)

'Get the information for this driving cycle

cyclename = InputBox("enter the name of this driving cycle (e.g. CBD #1)")

start_sample = ActiveSheet.Cells(4 + cycleouterloop, 4)

start_sec = ActiveSheet.Cells(4 + cycleouterloop, 5)

end_sample = ActiveSheet.Cells(4 + cycleouterloop, 6)

end_sec = ActiveSheet.Cells(4 + cycleouterloop, 7)

diameter = ActiveSheet.Cells(4 + cycleouterloop, 8)

dilutionratio = ActiveSheet.Cells(4 + cycleouterloop, 9)

'Initialize the counters and pointers used in program

```
numsamples = end_sample - start_sample + 1
wcol = start_col + data_col + 2 + cycleouterloop
wrow = 1
rrow = start_row + (start_sec - 1) * 10
workingcol = start_col

'write simple 3 row header to identify driving cycle

ActiveSheet.Cells(wrow, wcol) = "raw counts arranged into driving cycles"
wrow = wrow + 1
ActiveSheet.Cells(wrow, wcol) = cyclename
wrow = wrow + 1
ActiveSheet.Cells(wrow, wcol) = diameter
wrow = wrow + 1

If (smps_sample_length - start_sec > cyclelen Or numsamples = 1) Then
'Just one sample in this cycle
nodata = InputBox("cycle is measured in only part of one SMPS sample , data not written")
GoTo 100
End If

    smpssample = ActiveSheet.Cells(sample_row, workingcol)

' loop until the starting SMPS sample number for the driving cycle is found in the file

    Do While (smpssample - start_sample) <> 0

        workingcol = workingcol + 1
        smpssample = ActiveSheet.Cells(sample_row, workingcol)
        If workingcol > data_col Then ' the sample number entered did not match any in the file
            nodata = InputBox("the sample is not included in this file")
            Exit Do
        End If
    Loop

    smpstimestart = (ActiveSheet.Cells(sample_row + 2, workingcol))

For loop2 = 0 To ((cyclelen * 10) - 1)
    ActiveSheet.Cells(wrow, wcol) = ActiveSheet.Cells(rrow, workingcol)
    wrow = wrow + 1
    rrow = rrow + 1

    If rrow = 147 + smps_sample_length * 10 Then
        rrow = 147
    '    samplenum = samplenum + 1
        workingcol = workingcol + 1
    End If
Next loop2

' If end SMPS sample number did not match the entry, notify user to check setup
smpssample = ActiveSheet.Cells(sample_row, workingcol)
If smpssample <> end_sample Then
    nodata = InputBox("end sample number did not match")
End If
```

' AT THIS POINT, DATA FROM ONE FULL DRIVING CYCLE AT ONE DIAMETER HAS BEEN
WRITTEN INTO THE FILE, NEXT SECTION CONVERTS THIS DATA TO CONCENTRATIONS
' WHILE KEEPING THE RAW DATA COLUMNS FOR FUTURE REFERENCE

'this part computes the 1 second panel mode concentrations for the diameters used in the ARB
Phase1B study

'Note, conversions are flow rate specific for DMA and CPC 14.0/1.45 LPM CPC in high flow
mode (flow rate 30 cm³/min).

' using 10 of the 0.1-second CPC data points, we accumulate 1 second of data. flows are
converted to one second basis using conversion 60 sec/min.

' the CF_DMA was computed in the Mathcad program using the flowrates stipulated above
'the variable diameter was input as part of user input above and used again here.

If diameter - 8 = 0 Then

multiplier = diam8

Elseif diameter - 20 = 0 Then

multiplier = diam20

Elseif diameter - 40 = 0 Then

multiplier = diam40

Elseif diameter - 50 = 0 Then

multiplier = diam50

Elseif diameter = 80 Then

multiplier = diam80

Elseif diameter - 100 = 0 Then

multiplier = diam100

Elseif diameter = 140 Then

multiplier = diam140

Else

' diameter does not match any computed correction factors")

End If

'DO CONVERSIONS AND WRITE INTO FILE, 2 COLUMNS PER DRIVING CYCLE, ONE IS
TIME OF DAY, SECOND IS DATA

'Loop for one driving cycle and write to column in same worksheet as raw data

wcol_final_data = wcol + 3 * cycleouterloop + 8

ActiveSheet.Cells(1, wcol_final_data + 1) = "RefDesig"

ActiveSheet.Cells(2, wcol_final_data + 1) = "diameter"

ActiveSheet.Cells(3, wcol_final_data + 1) = "start time>>"

'write driving cycle definitions as part of row definitions/header for each

ActiveSheet.Cells(1, wcol_final_data + 2) = cyclename

ActiveSheet.Cells(1, wcol_final_data + 3) = "DR corrected"

wrow = wrow + 1

ActiveSheet.Cells(2, wcol_final_data + 2) = diameter

ActiveSheet.Cells(2, wcol_final_data + 3) = diameter

wrow = wrow + 1

' include the start time of the driving cycle and panel data at the top of each of two data columns
(non-DR corrected and DR-corrected data)

cyclestarttime = TimeSerial(0, 0, start_sec - 1) + smpstimestart

ActiveSheet.Cells(3, wcol_final_data + 2) = FormatDateTime(cyclestarttime, vbLongTime)

ActiveSheet.Cells(3, wcol_final_data + 3) = FormatDateTime(cyclestarttime, vbLongTime)

```
For concloop = 0 To cyclelen - 1
'loop for driving cycle length
accum1sec = 0
'loop for each second
  For doonesec = 0 To 9
    accum1sec = accum1sec + ActiveSheet.Cells(4 + doonesec + concloop * 10, wcol) ' sum ten
of the 0.1 second counts
  Next doonesec

  ' write time of day for each second of data
  cycledatotime = TimeSerial(0, 0, concloop) + cyclestarttime
  ActiveSheet.Cells(concloop + 4, wcol_final_data + 1) = FormatDateTime(cycledatotime,
vbLongTime)
  'write converted concentration (pre dilution-ratio correction)
  ActiveSheet.Cells(concloop + 4, wcol_final_data + 2) = multiplier * accum1sec
  'write dilution-ratio corrected converted concentration
  ActiveSheet.Cells(concloop + 4, wcol_final_data + 3) = multiplier * accum1sec * dilutionratio

Next concloop
100 Next cycleouterloop
'write column for row definitions (moved in to loop to put header on each driving cycle
'ActiveSheet.Cells(1, start_col + data_col + 11) = "RefDesig"
'ActiveSheet.Cells(2, start_col + data_col + 11) = "diameter"
'ActiveSheet.Cells(3, start_col + data_col + 11) = "start time>>"
End Sub
```

A.5 References Cited

- Fuchs, N., 1963. On the Stationary Charge Distribution on Aerosol Particles in a Bipolar Ionic Atmosphere. *Geophys. Pura Appl.*, 56(185).
- Knutson and Whitby, 1975. Aerosol Classification by Electrical Mobility: Apparatus, Theory and Applications. *Journal of Aerosol Science*, 6(6): 443-451.
- Nanzetta-Converse, M.K. (2004) Roadside Ultrafine and Nanoparticle Particle Number Distributions in Northern Central Valley, CA and Relationships to Meteorology and Traffic. Ph.D. thesis, University of California Davis, Civil & Environmental Engineering, March 2004.
- Seinfeld, J. and Pandis, S., 1998. Atmospheric chemistry and physics of air pollution. Wiley, New York, 738 pp.
- TSI, 2002a. Model 3936 SMPS (Scanning Mobility Particle Sizer) Instruction Manual. TSI.
- TSI, 2002b. Model 3025A Ultrafine Condensation Particle Counter Instruction Manual P/N 1933762, Revision 1 July 2002.
- Wiedensohler, A. and Fissan, H., 1988. Aerosol Charging in High Purity Gases. *Journal of Aerosol Science*, 19(7): 867-870.

Appendix B: Scanning Mobility Particle Sizer (SMPS) Panel Mode Data Number Concentration Plots by Individual Driving Cycle

NOTE: These data are not corrected for dilution ratio.

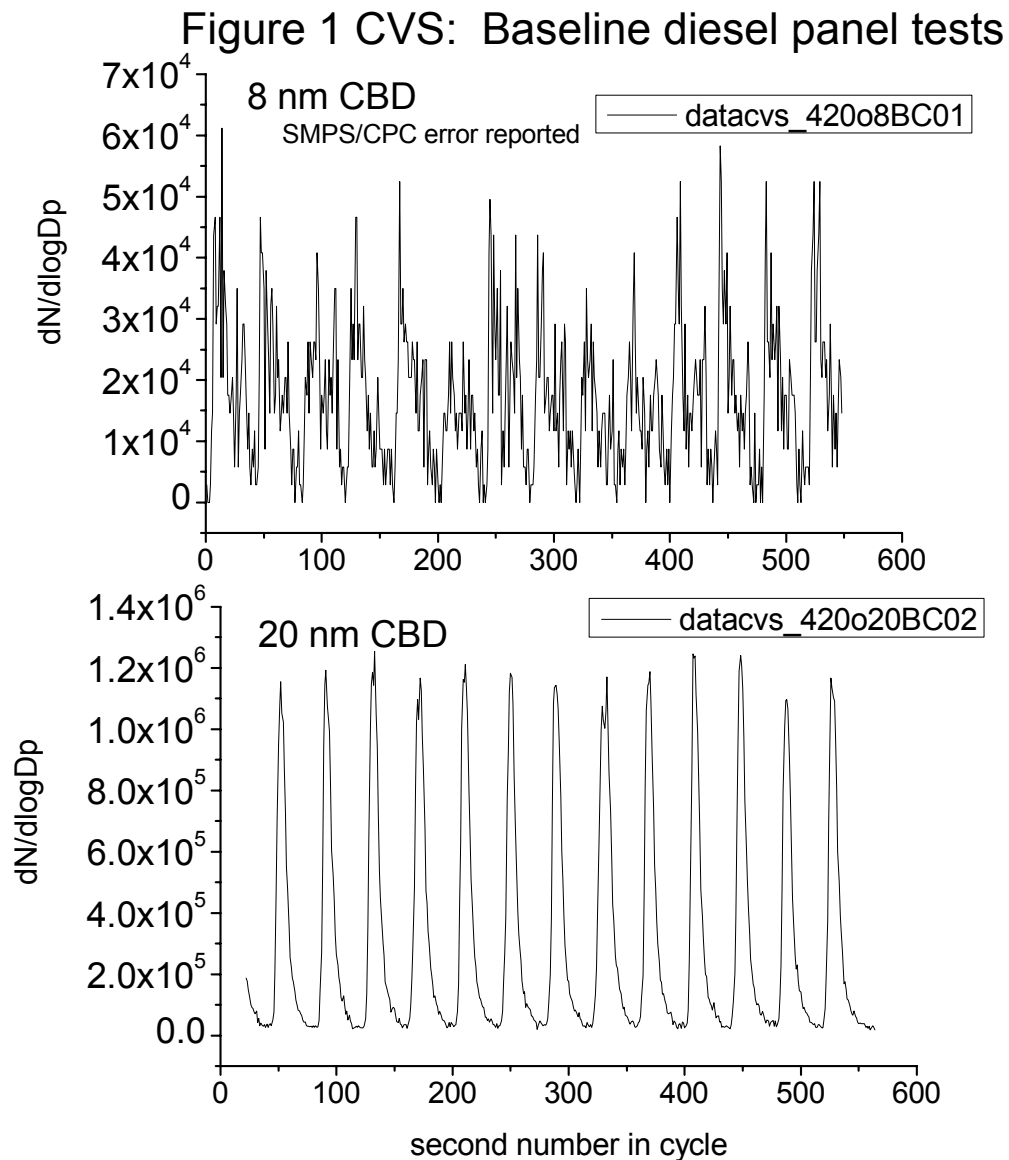


Figure 1 Minidluter: Baseline Diesel Panel tests.

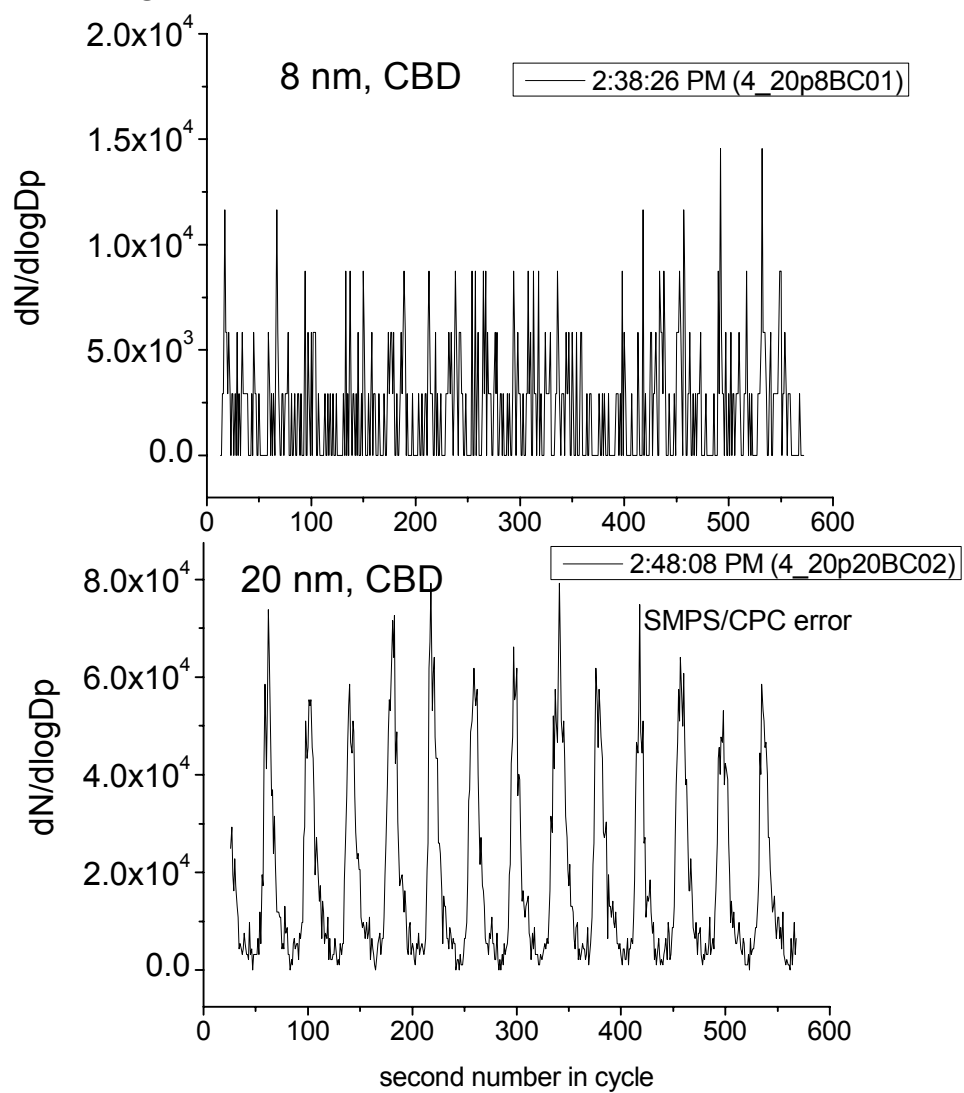


Figure 2 CVS: CNG bus 8 nm on CBD cycle

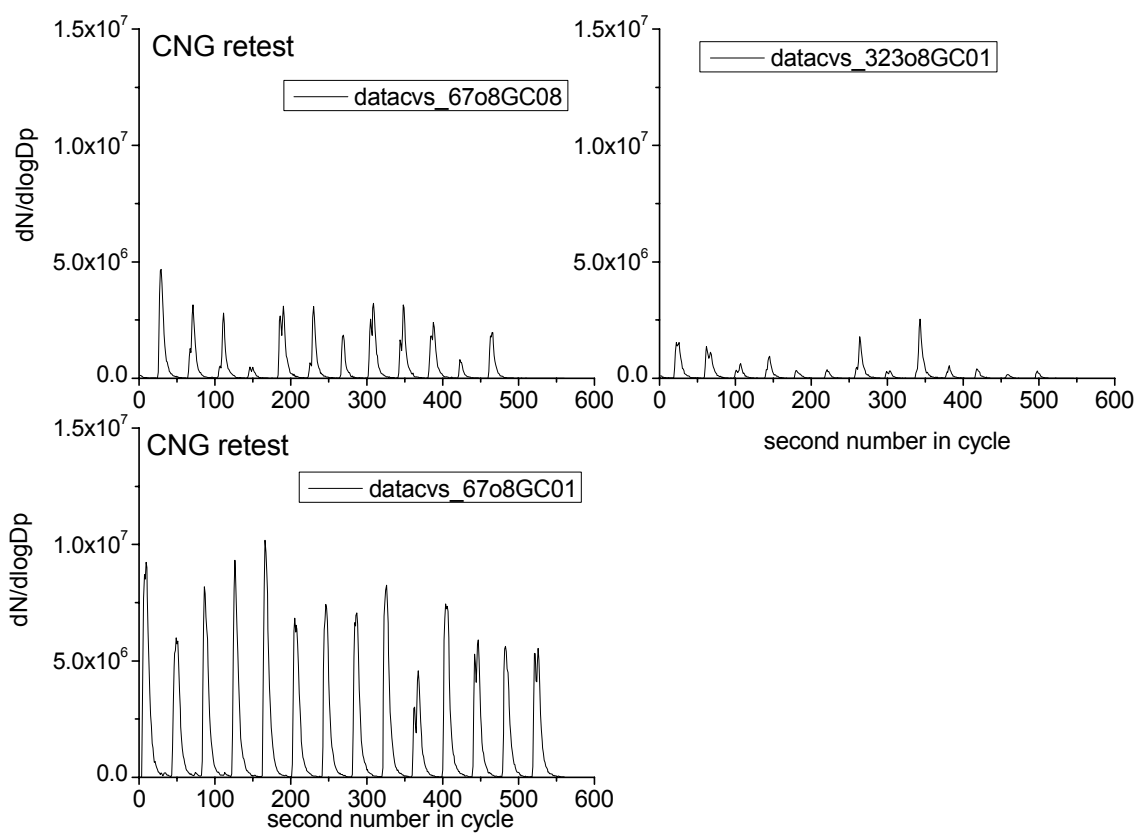


Figure 2 Minidiluter: CNG bus 8 nm on CBD cycle

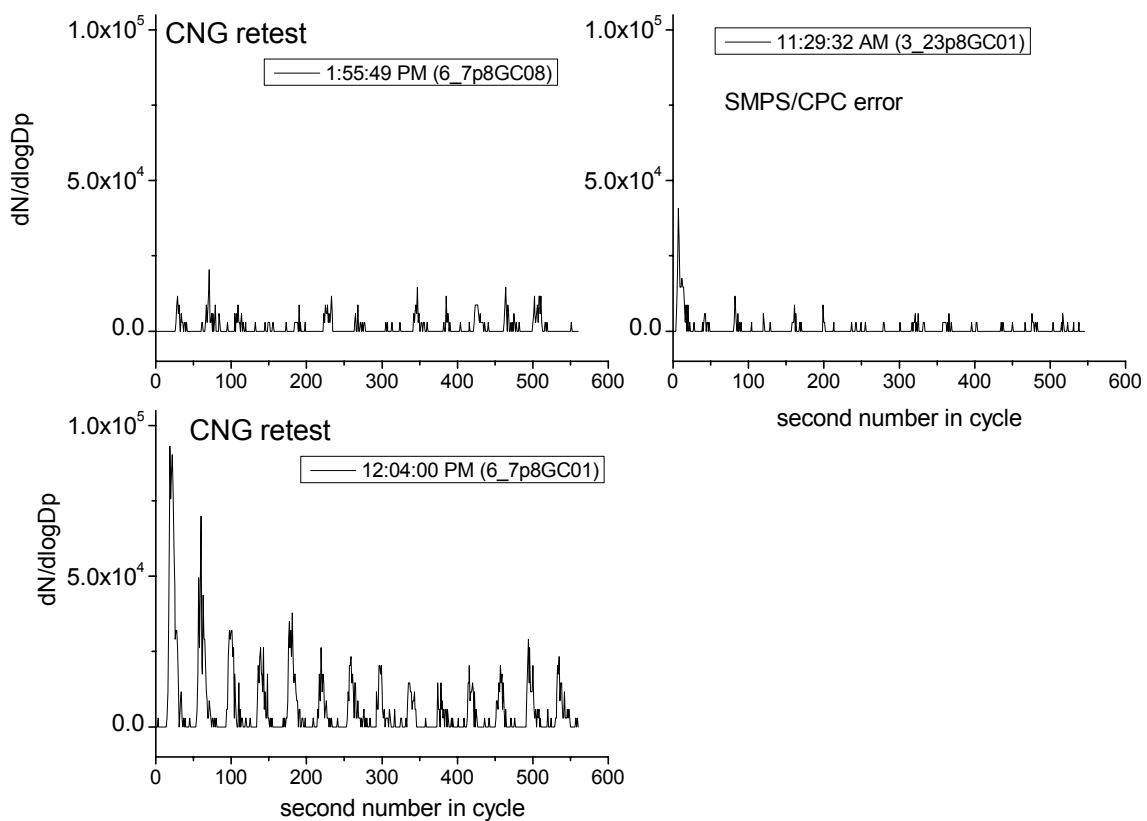


Figure 3 CVS: CNG test at 20 nm on CBD

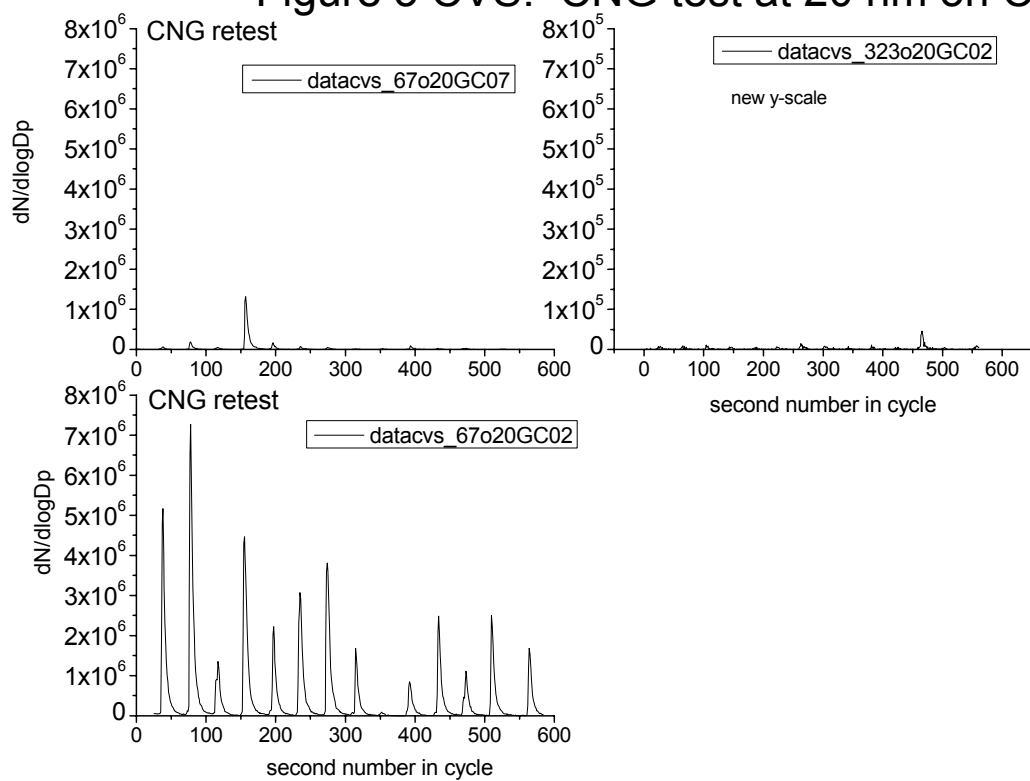


Figure 3 Minidiluter: CNG test at 20 nm on CBD

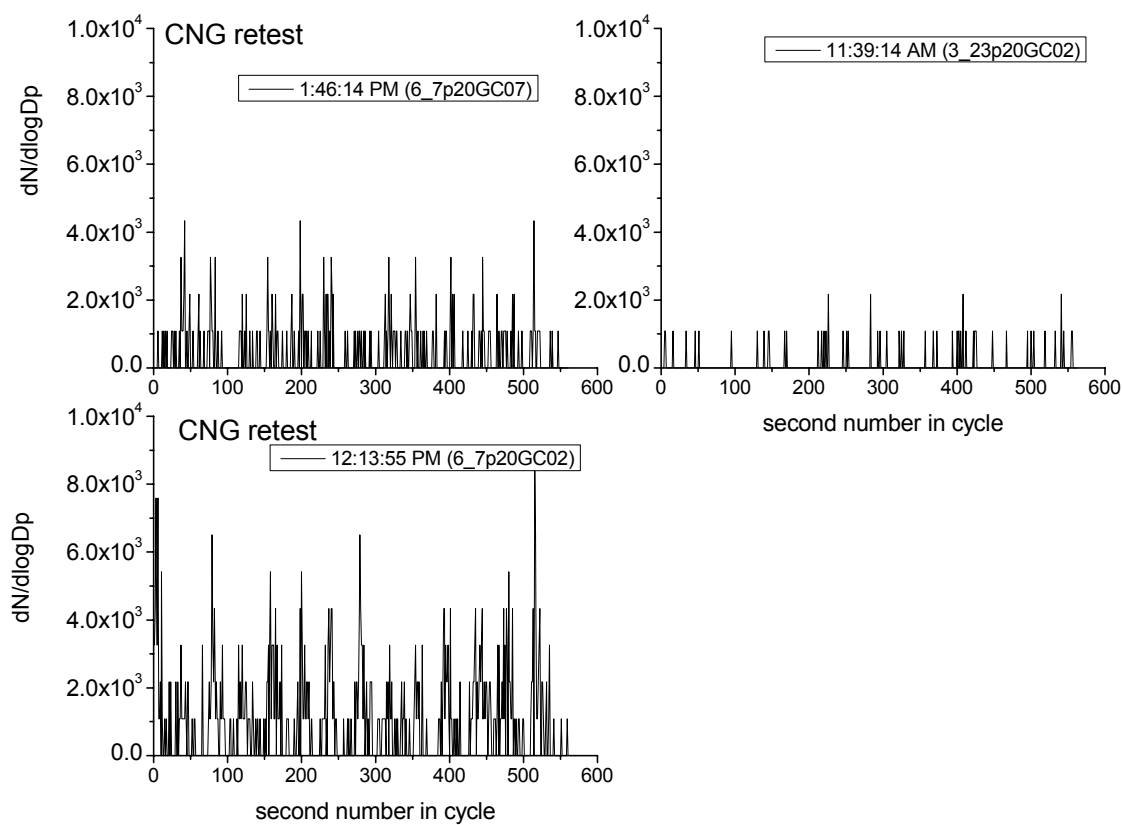


Figure 4 CVS: CNG bus tested on 80 nm CBD cycle

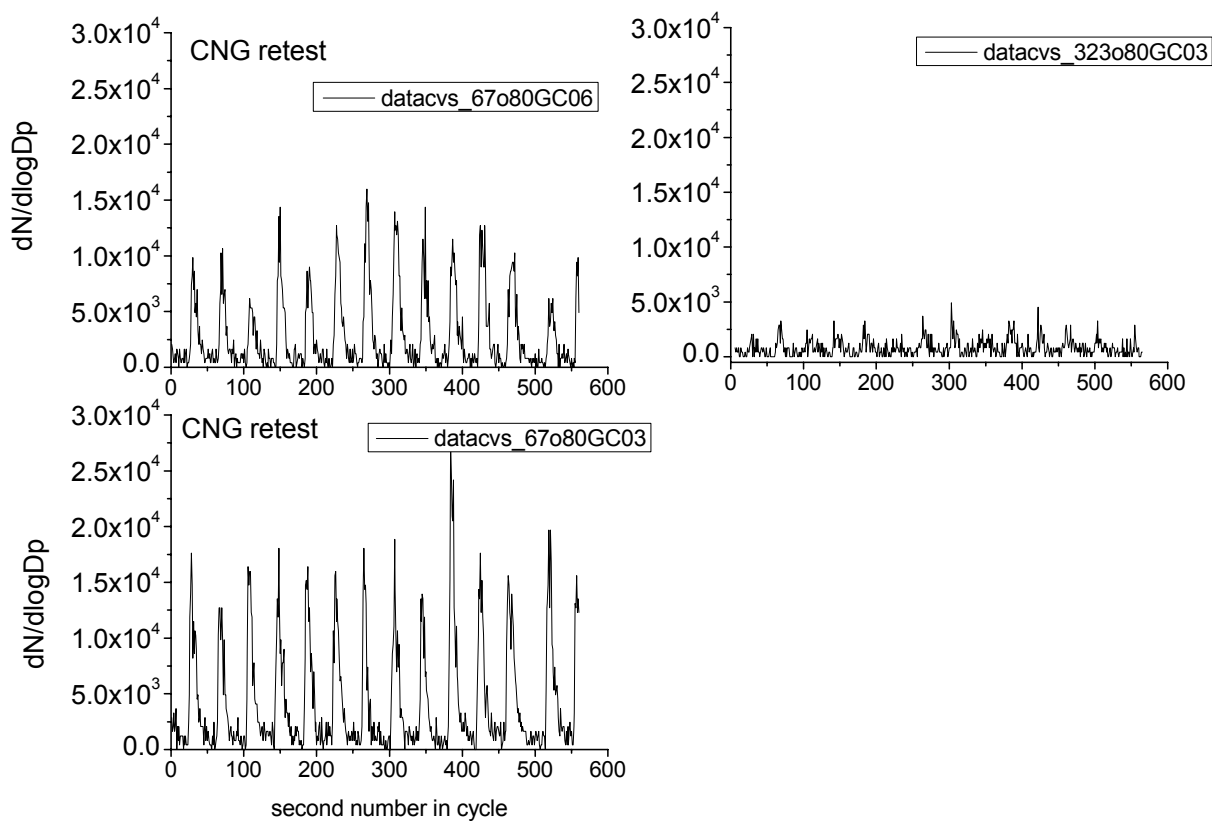


Figure 4 Minidiluter: CNG bus tested on 80 nm CBD cycle

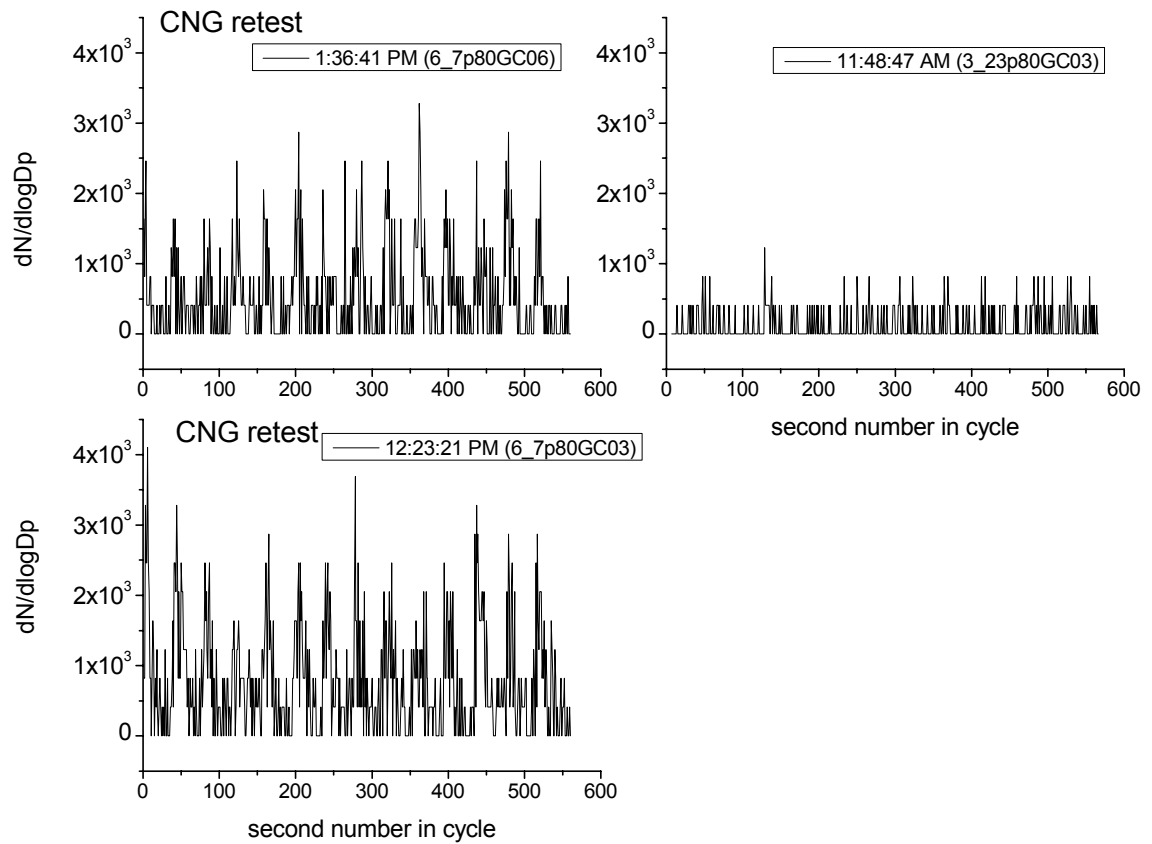


Figure 5 CVS: CNG bus on CBD cycle at 140 nm

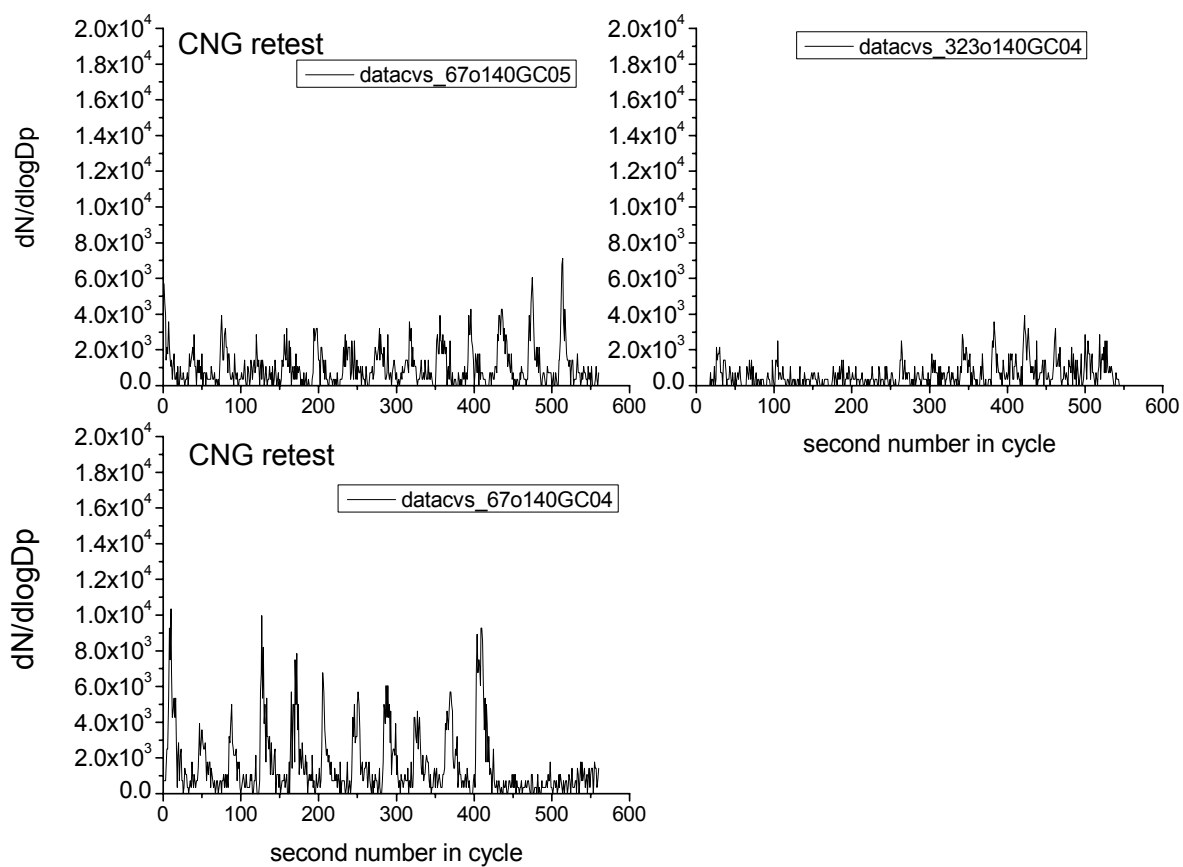


Figure 5 Minidiluter: CNG bus on CBD cycle at 140 nm

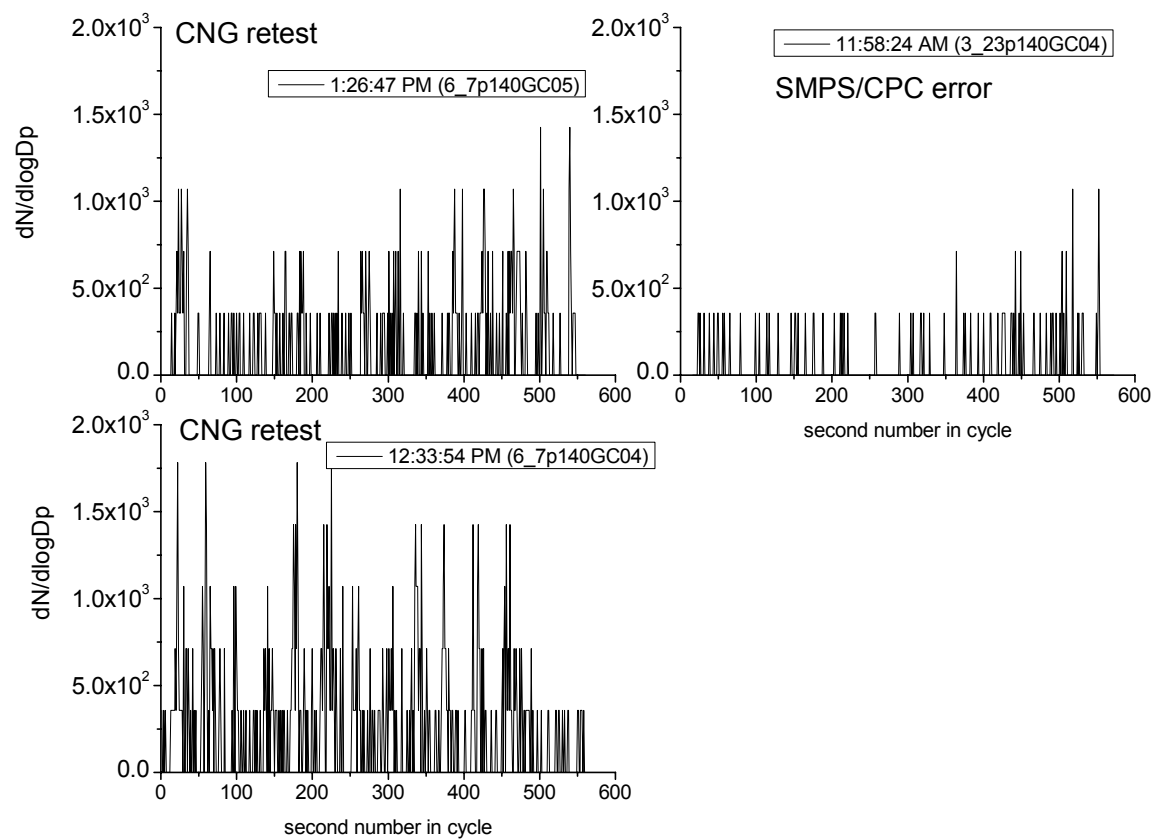


Figure 6 CVS: CNG tested on NY bus cycle

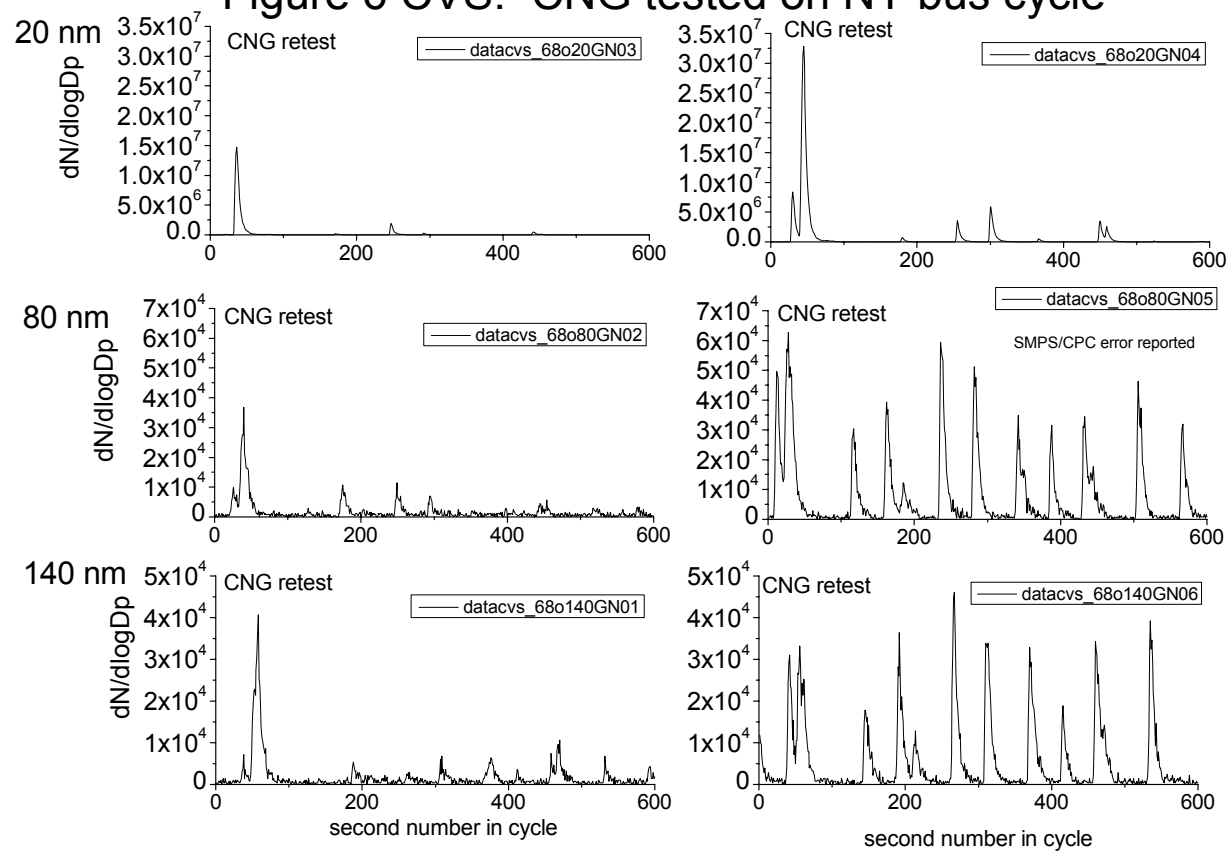


Figure 6 Minidiluter: CNG tested on NY bus cycle

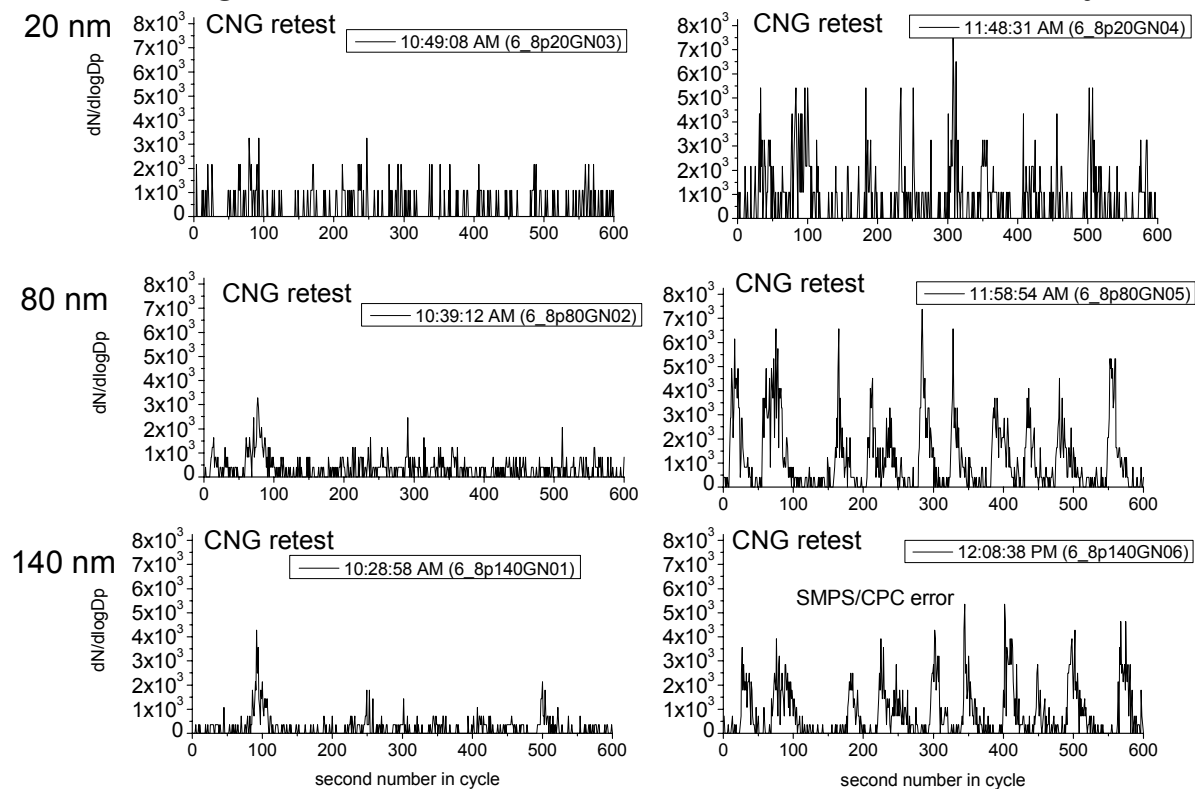


Figure 7 CVS: CNG bus on UDDS cycle

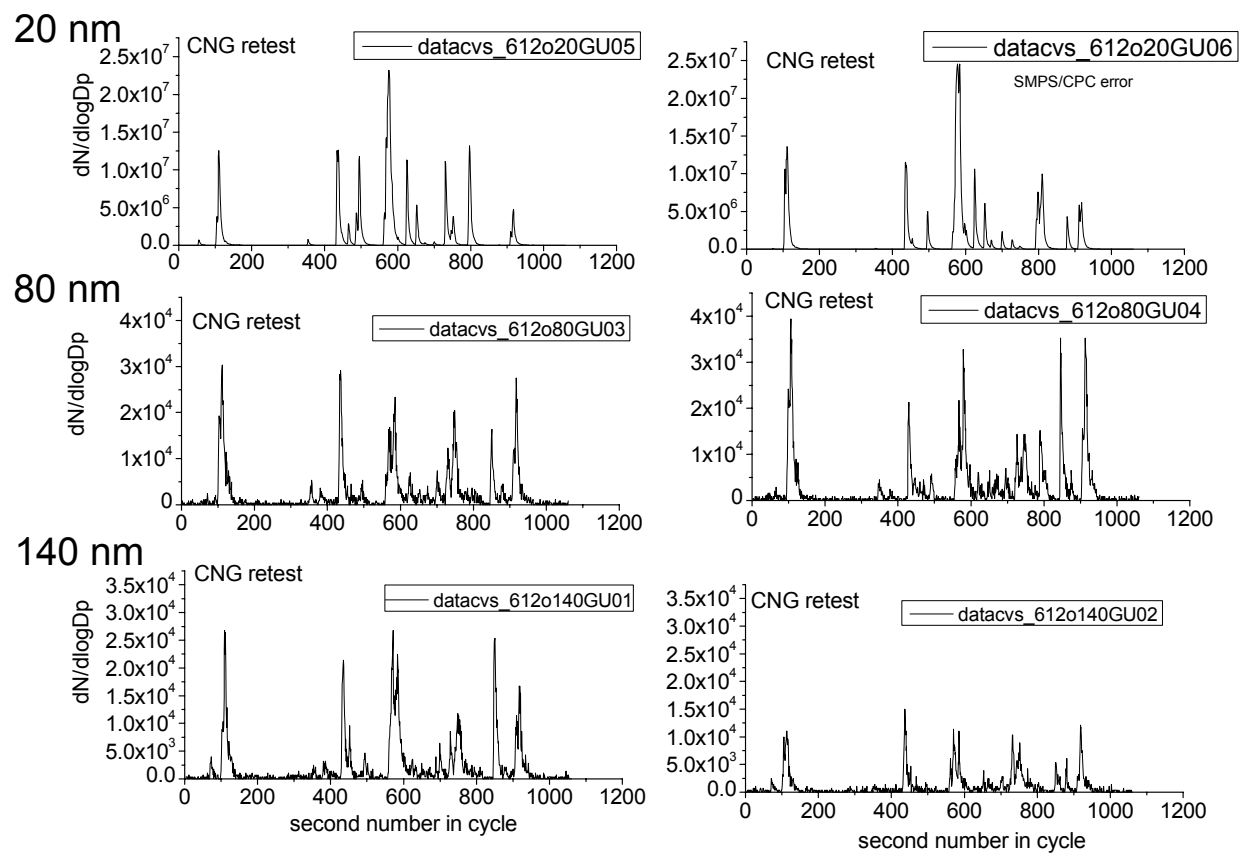


Figure 7 Minidiluter: CNG tested on UDDS bus cycle

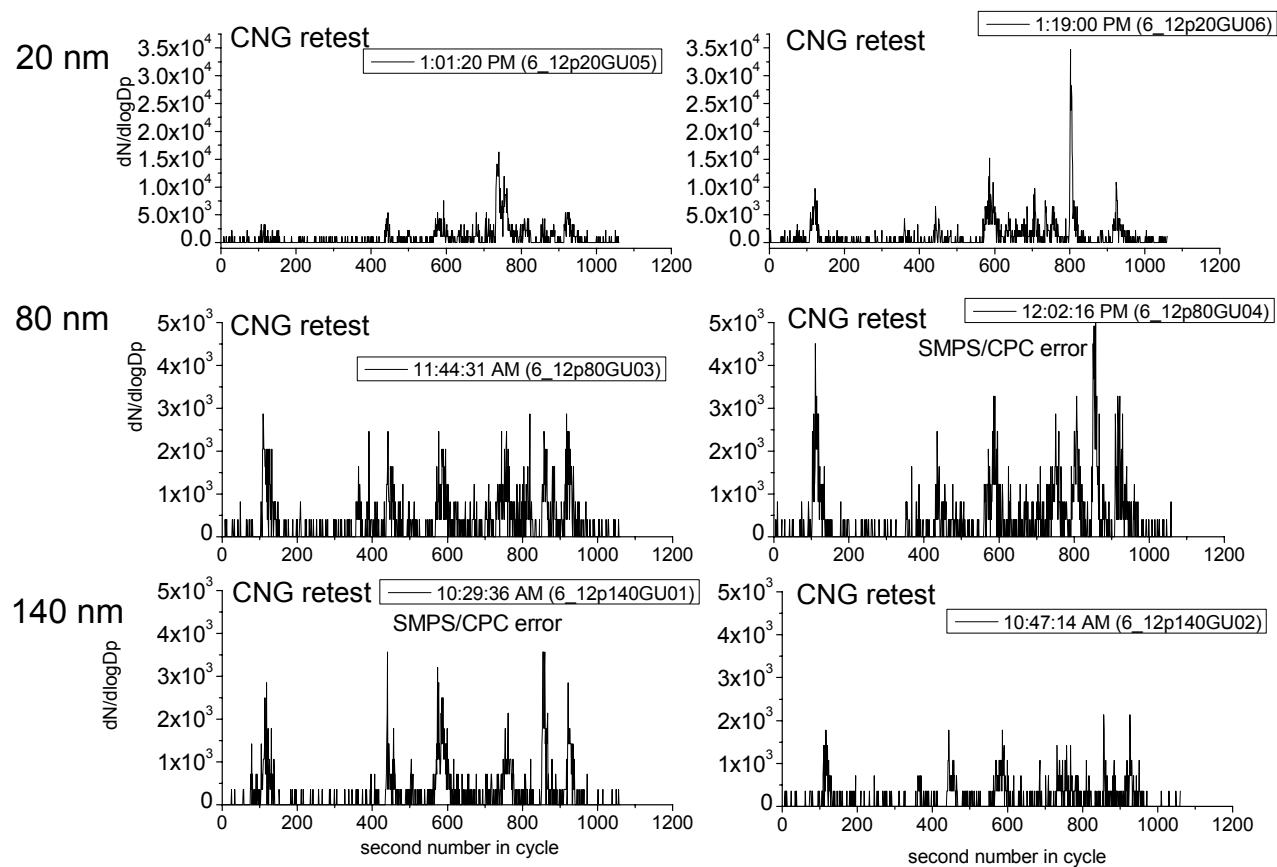


Figure 8 CVS: Trap Diesel 8 nm test on CBD

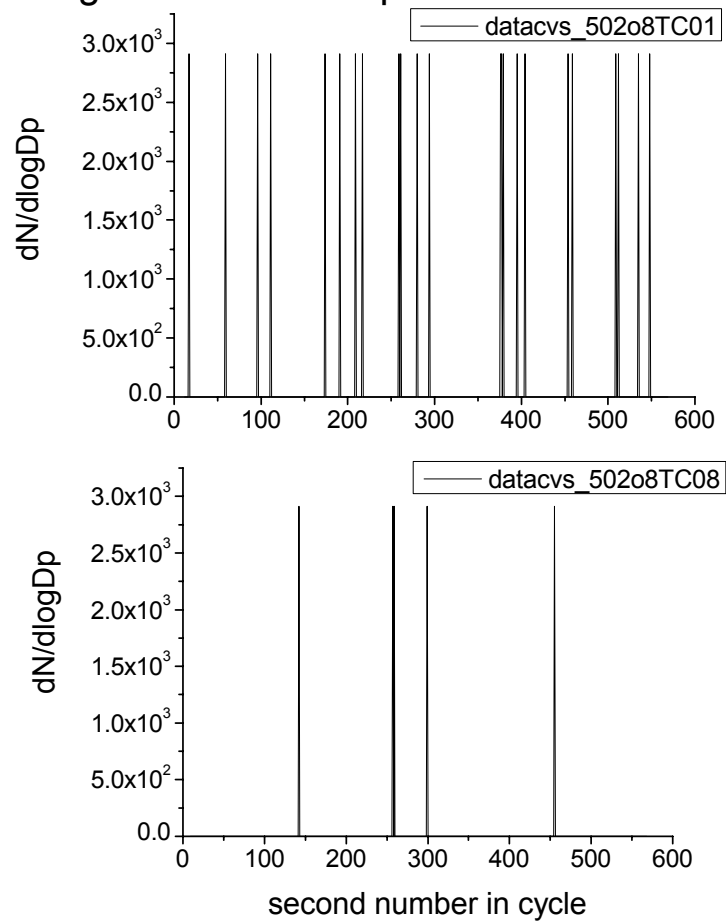


Figure 8 Minidiluter: Trap Diesel 8 nm test on CBD

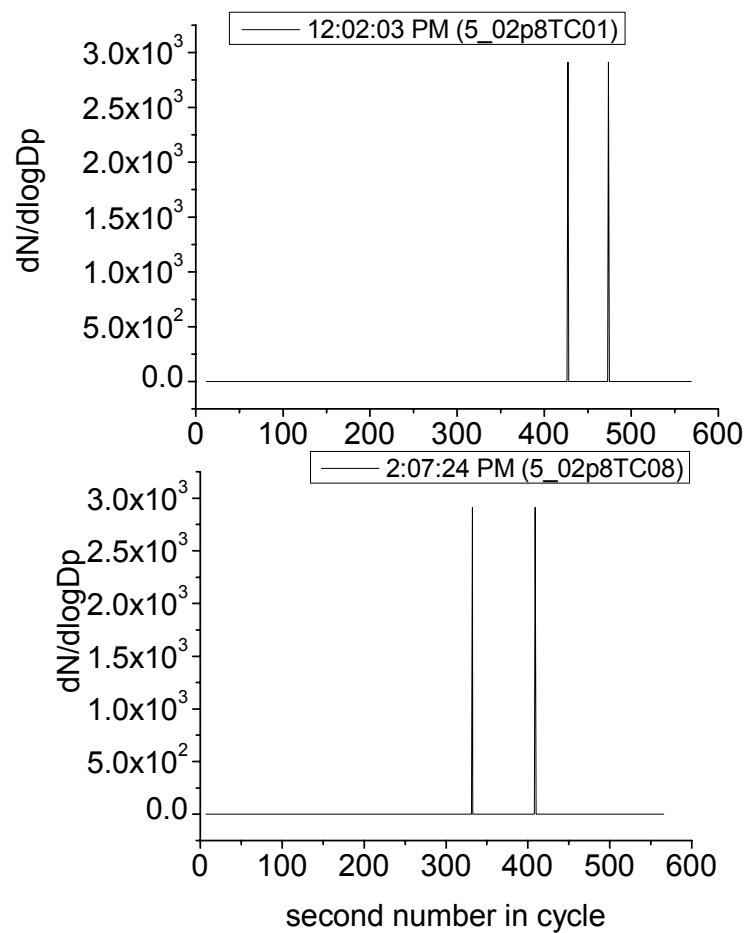


Figure 9 CVS: Trap diesel on CBD cycle

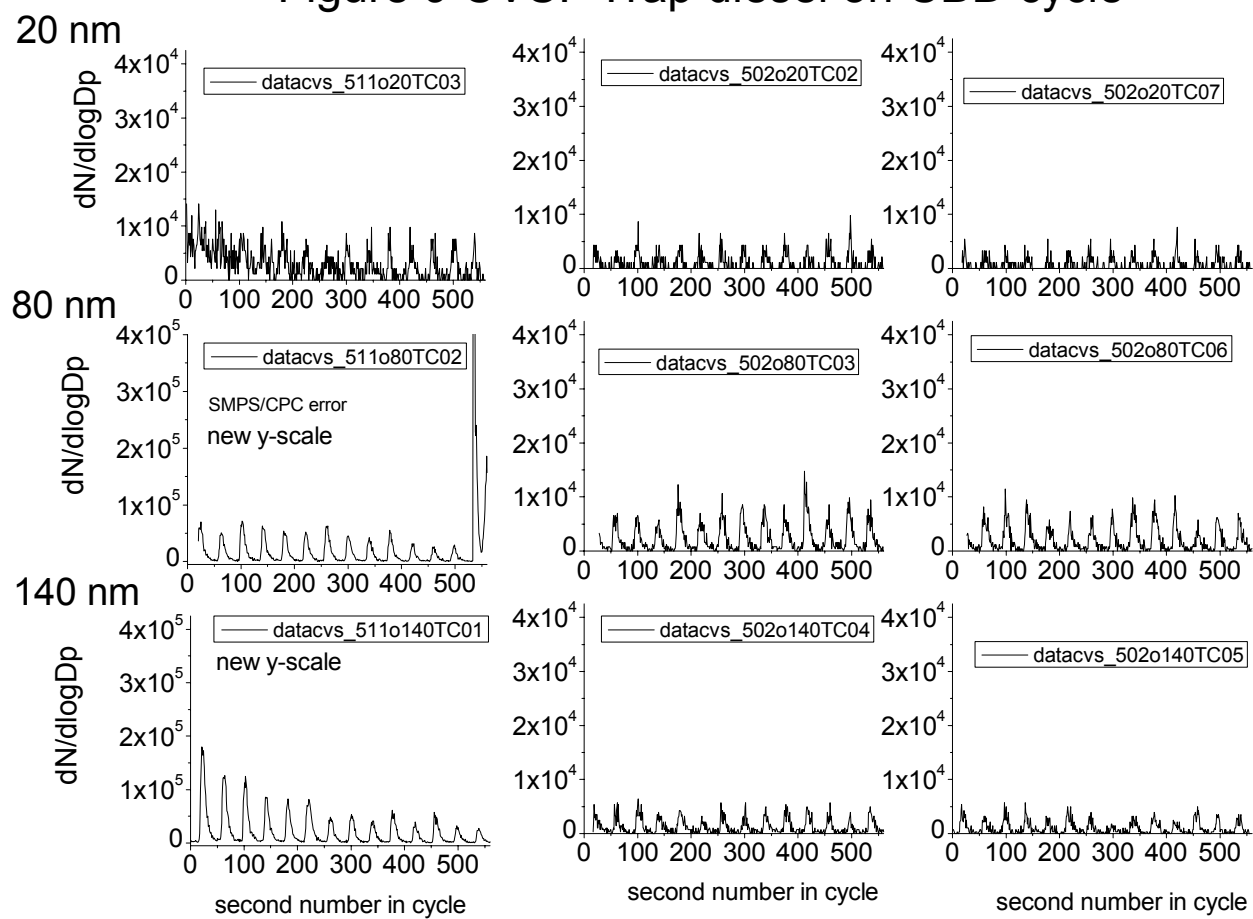


Figure 9 Minidiluter: Trap diesel on CBD cycle

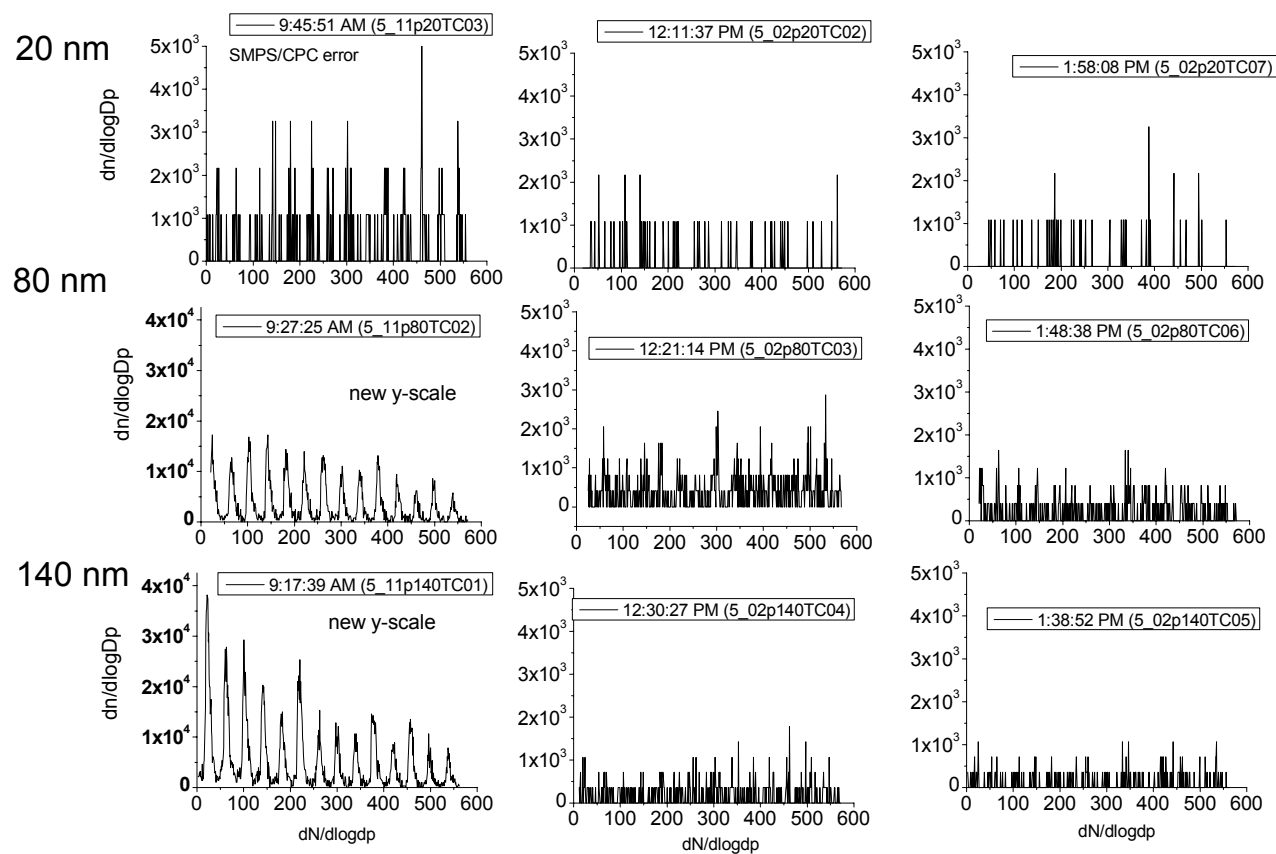


Figure 10 CVS: Trap Diesel driven on NY bus cycle

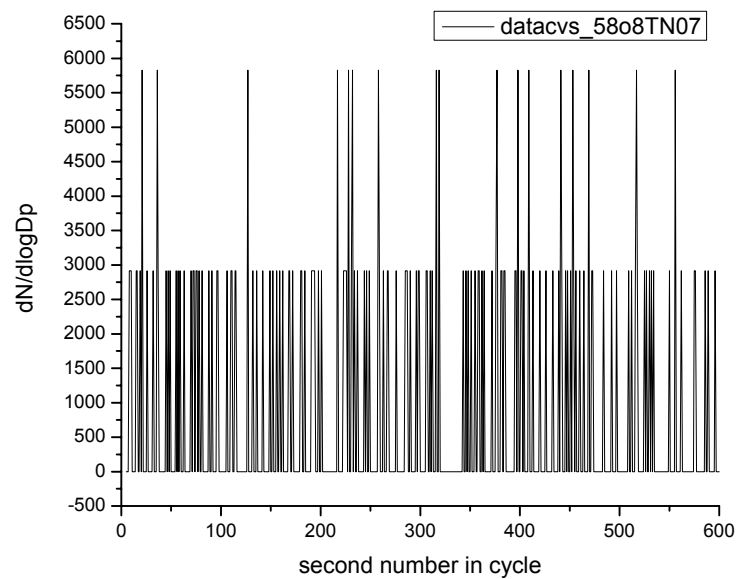


Figure 10 Minidiluter : Trap Diesel driven on NY bus cycle

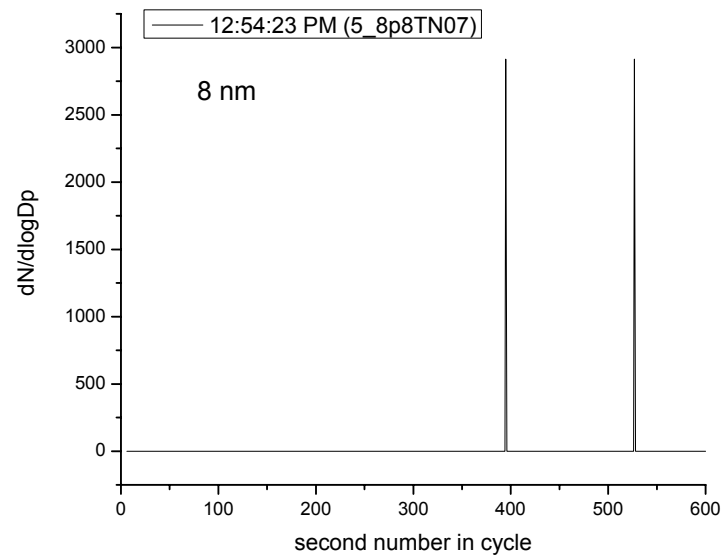


Figure 11 CVS: Trap Diesel on NY bus cycle

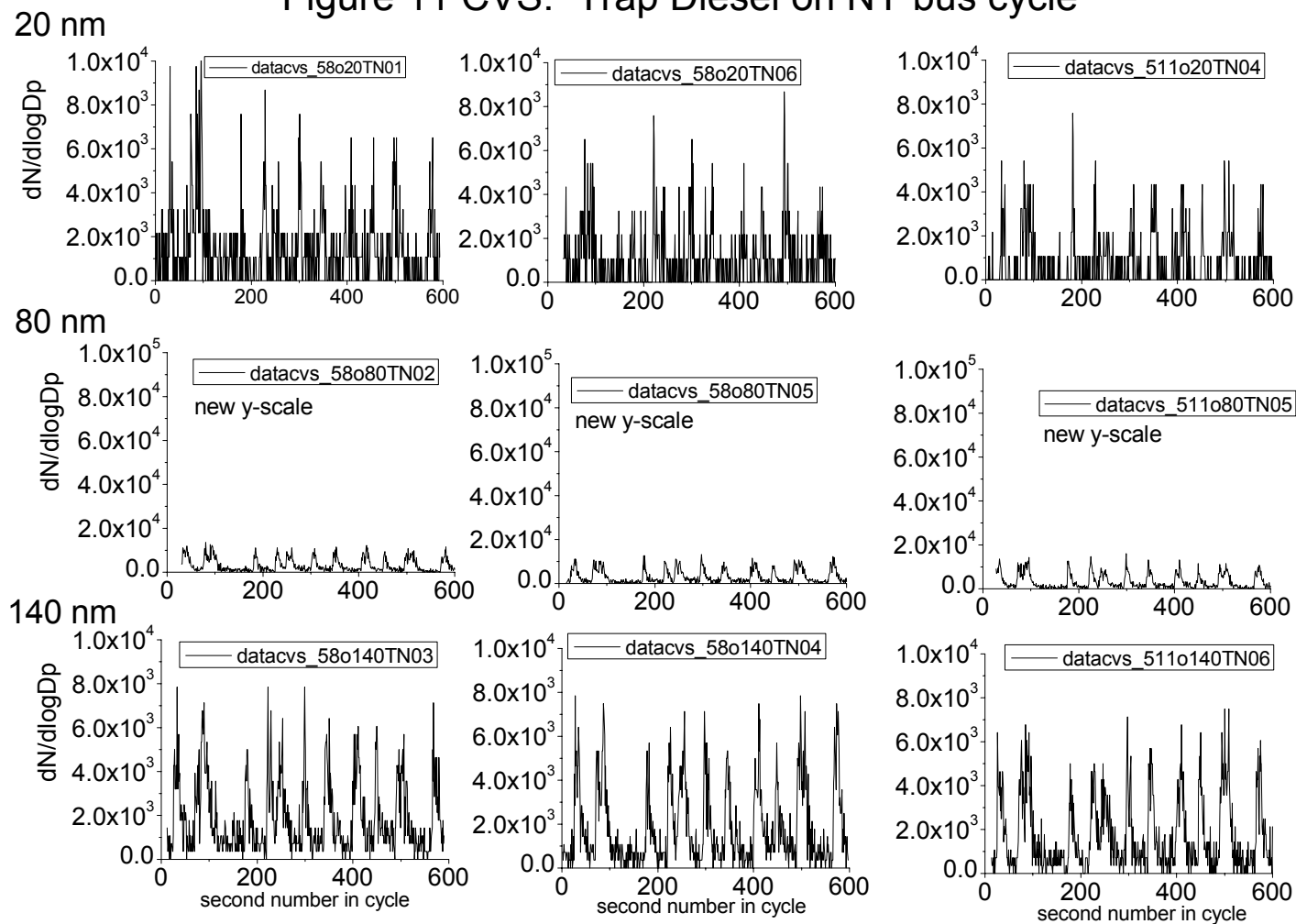


Figure 11 Minidiluter: Trap Diesel on NY bus cycle

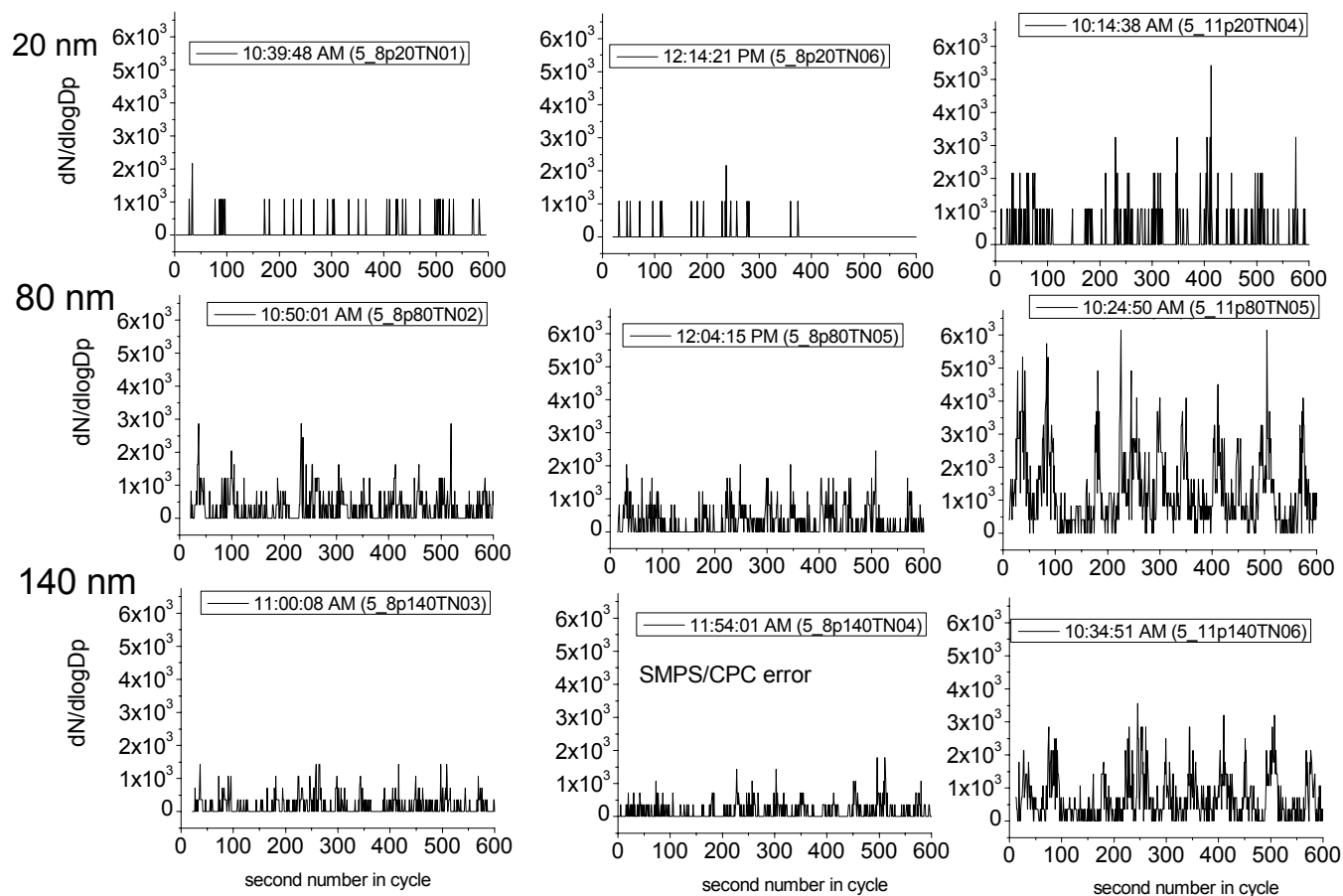


Figure 12 CVS: Trap Diesel driven on UDDS

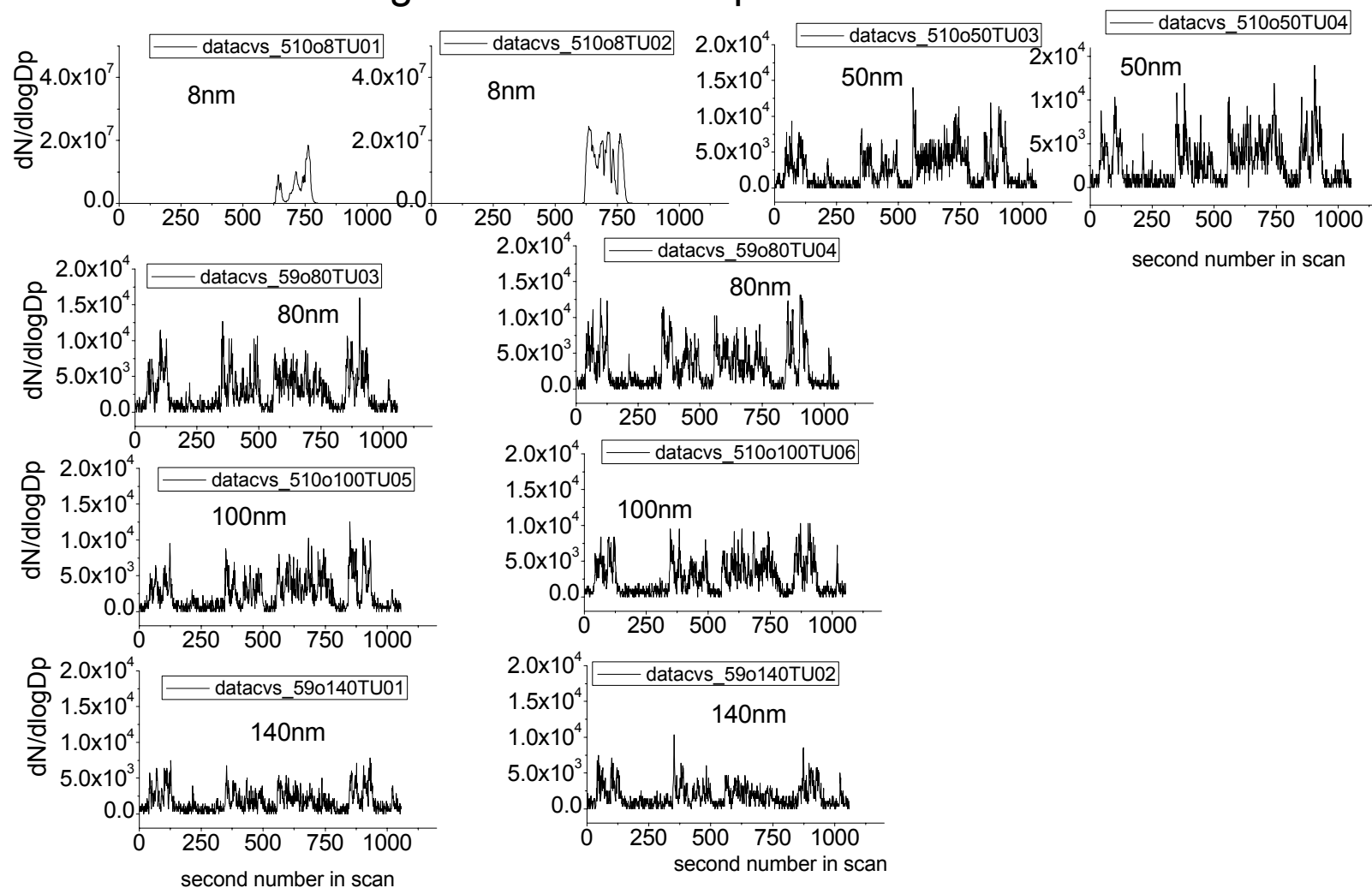


Figure 12 Minidiluter: Trap Diesel driven on UDDS

